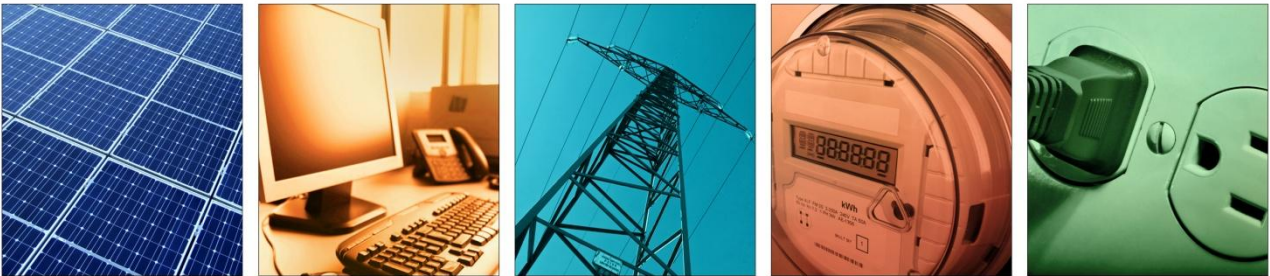


Image Processing Occupancy Sensor (IPOS) Final Project Report

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Abstract

This project report describes project activities for a novel image processing occupancy sensor (IPOS) developed by NREL's Commercial Buildings research group. The sensor is based on commercially available embedded hardware that is widely used by the smart phone industry. It leverages mature open-source computer vision software libraries and uses modern software engineering techniques and firmware development technologies. Compared to traditional passive infrared and ultrasonic-based motion sensors currently used for occupancy detection, IPOS has shown the potential for improved accuracy and a richer set of feedback signals for occupant-optimized lighting, daylighting, temperature setback, ventilation control, and other uses. This report describes findings from initial testing of an enhanced prototype and discusses the

methodology, results, potential use cases, and recommendations for future developments.

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Executive Summary

This report documents development and progress for an advanced image processing occupancy sensor (IPOS) technology developed at the National Renewable Energy Laboratory (NREL). For decades, occupancy sensors have been required by building code to minimize energy use. They commonly control lights in commercial buildings by turning them off in unoccupied areas after a preset time delay. Motion-based sensors can falsely identify vacancy when occupants are stationary, turning lights off prematurely and undermining the acceptance of the system. Because of detection limitations due to uncertainty –infer occupancy by assessing motion, time delays are set typically in the range of 15-20 minutes, which reduces energy savings potential. In many cases, occupants or building maintenance staff purposely alter or disable occupancy sensors in response to complaints, which invalidates the building code mandate.

IPOS detects and assesses human occupancy in areas, rooms, and buildings to potentially localize and optimize lighting, daylighting, and heating, ventilating, and air conditioning (HVAC). Unlike traditional passive infrared (PIR) or ultrasonic occupancy sensors, which infer occupancy based only on motion, IPOS uses digital image-based monitoring to detect and classify various aspects of occupancy, including the presence of occupants regardless of motion, number, location, and activity levels of occupants, as well as the illuminance properties of the monitored space.

IPOS leverages the recent availability of low-cost, powerful embedded computing platforms, computer vision software technology, and camera elements. The image-based analysis for occupancy detection is the result of the aggregation of three functional elements of detection: a motion-based component and two motion-independent components. Motion detection is performed through analysis of multiple frames over time; motion-independent detection is performed through image recognition algorithms that identify the presence of human faces or people in the monitored space. Aggregation of the three component analysis provides an occupancy determination that is potentially more accurate than motion-only based technologies. Along with higher detection accuracy, IPOS uses an adaptive time delay that is typically lower than fixed time delays commonly used by current motion sensors, which may enable higher energy savings.

Whereas traditional technologies require a motion sensor in each monitored space, IPOS can capture images of larger areas, and may be able to replace several traditional occupancy sensors by segmenting the images into several¹ virtual control zones. The zones can be analyzed individually, enabling large spaces² to be monitored and controlled through a single sensor, with potential cost reduction benefits resulting from multiple functions and a reduced number of sensors per covered area.

¹ Up to eight user-selectable virtual zones, or up to 16 through software configuration.

² Coverage area depends on camera sensor field of view.

IPOS also uses computer vision techniques to detect occupancy density, number and location of occupants, illuminance levels, and occupant activity levels. This capability has potential for new sophisticated control strategies to minimize building energy use and to improve daylight harvesting.

Currently, occupancy sensors and daylight harvesters are two distinct sensors, requiring redundant packaging, higher installation labor costs, higher commissioning costs, and higher maintenance of lighting controls. One major advantage of IPOS is it can provide both functions simultaneously, which may reduce overall component and installation labor costs.

Preliminary functional tests evaluated the accuracy of IPOS in the upper 90% range, compared to 70.4% and 76.9% from two commercially available PIR sensors evaluated in an earlier study [6].

Energy savings potential was evaluated through vacancy period comparisons between IPOS and the model of a typical PIR sensor. IPOS exhibited consistently better performance than the model. IPOS vacancy time was 25.7% greater than the traditional PIR occupancy sensor model during core weekday hours with time delay setting of 15 minutes, an indication of greater energy savings potential.

IPOS research generated two patent applications, with research shared through several initiatives, mainly webinars and conferences. In addition, IPOS was the recipient of the prestigious 2013 R&D 100 Award, which recognizes the 100 most technologically significant innovations of the year.

Licensing and commercialization efforts are underway with several companies. The IPOS project partnered with NREL's Commercialization and Technology Transfer division, whose mission is to accelerate the commercialization of NREL-developed technologies and products under the protection of either nonexclusive or exclusive rights through several key activities, including Technology Partnership Agreements, innovation management, and licensing.

Most of NREL's licenses are royalty-bearing, nonexclusive, and contain annual performance milestones; however, NREL may grant an exclusive license when such a license is the best mechanism for maximizing a technology's market impact. For IPOS, NREL Commercialization and Technology Transfer is devising a strategy of multiple nonexclusive licenses of the technology to broaden influence, maximize taxpayer investment, and at the same time to reduce risks.

Because of the cost reduction prospect and energy savings that IPOS might enable, additional key applications have been identified, with recommendations for future developments:

- Daylight harvesting and occupancy control
- Daylight commissioning tool

- Occupancy and event logger, occupancy analysis
- Light logging/lighting sub-metering
- Interactive exhibits
- Demand controlled ventilation control
- Space planning and management

Terms and Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BACnet	building automation and controls network
BAS	building automation system
CREED	Colorado Center for Renewable Energy Economic Development
CSV	comma separated value
DCV	demand controlled ventilation
DoD	U.S. Department of Defense
EC	electrochromic
EMS	energy management system
ESI	Energy Systems Integration
GCL+	general control language plus
HOG	histogram of oriented gradient
HVAC	heating, ventilation, and air conditioning
IPOS	image processing occupancy sensor
LED	light emitting diode
OpenCV	open source computer vision
PIR	passive infrared
ROI	region of interest
RSF	Research Support Facility

1 Project Background

Occupancy sensing has been required by energy codes and deployed in buildings for decades. Most current occupancy sensors detect motion, providing occupancy feedback for control of lights either through local control or through a building automation system (BAS) or an energy management system (EMS) [1]. The fundamental operating principle of detection, based on motion, limits traditional occupancy technology performance as described in the following two examples. Occupants reading or working at their computers may not be detected if little³ or no motion is registered for long periods of time, causing lights to be switched off. Conversely, blinds moving in a vacant office could cause lights to be turned on unnecessarily. In these situations, the occupancy sensors may be intentionally disabled by users or by building maintenance staff (following user complaints) to avoid disruptions and dissatisfaction, restricting or nullifying their energy-saving potential and the reason they were installed and commissioned. This translates to investments with no energy savings.

Motion detector manufacturers tend to mitigate performance limitations by providing time and sensitivity adjustments, which are left set at factory default levels, calibrated during the lighting commissioning process, and rarely re-evaluated during post-commissioning [2, 3]. The technology and the adjustments required to minimize user dissatisfaction often lead to missed energy savings opportunities. Other approaches to managing this imprecision involve more sophisticated techniques including fuzzy logic, probabilistic data processing, and other advanced signal processing methods [4, 5], which are still founded on the same main mechanism of motion detection as a method for inferring occupancy. An alternate and potentially more robust approach is the image processing occupancy sensor (IPOS), which represents a fundamental technology change from the traditional approach.

The project was funded by the U.S. Department of Energy Building Technologies Program in fiscal year (FY) 2011, and advanced with funding in cost-share from the Bonneville Power Administration (BPA) in FY 2012 and 2013. The prototype has been functional tested at NREL's Research Support Facility (RSF), used as an occupancy and door state logger at a large retail store, and for logging/metering lighting at a U.S. Department of Defense (DoD) building. Applied testing as an occupancy and daylighting control was performed at a wireless lighting controls company.

IPOS addresses several needs and gaps highlighted in the BPA EE Technology Roadmap. It also crosscuts with other areas of the Roadmap as a potential enabler of other technologies that require accurate and reliable occupancy sensing for improved building energy efficiency and occupancy comfort. The versatility of this research lends itself to multiple categories in the BPA EE Roadmap: Lighting; Electronics; HVAC; and Sensors Meters and Energy Management Systems. IPOS has potential to address the following gaps identified in the Roadmap:

³ Below a minimum sensitivity threshold level

Gap 1 - Cost and ease of accurately controlling lighting often leads to underutilized systems.

The technology and methods behind occupancy sensors available today have not changed fundamentally in decades and provide less than ideal performance. Often, occupancy-based controls are intentionally defeated to avoid disturbing the occupants. IPOS represents a new type of occupancy sensor enabling advanced control schemes to tailor energy consumption to actual building use; it addresses the fundamental deficiencies in occupancy sensing technologies and expands lighting and ventilation control. A building outfitted with IPOS can potentially provide significant benefits in other areas, such as:

- Reduced installation cost because fewer IPOS devices may cover larger areas than traditional occupancy sensors and can perform multiple functions.
- Reduced number of uncontrolled stand-alone devices operating when no occupant is present by identifying and classifying occupancy to actively manage temperature, ventilation, lighting, and plug loads.
- Optimized light quality as perceived by users as a result of more accurate, real-time measurements and responses produced by sensing and control algorithms.

Gap 2 - Cluster of independent sensors increases complexity of design and cost.

IPOS can capture traditional occupancy information in addition to new information that quantifies how zones are being used, which may be utilized by other control algorithms. Estimates of space illuminance using the same sensor can be performed via image processing. In certain sensing scenarios, it may be possible to reduce the number of occupancy sensors required to cover large areas. Furthermore, the IPOS offers the potential for security system integration, decreasing the overall cost of a control system in a building by consolidating multiple functions to the IPOS. The output of the IPOS can be made available via standardized communication protocols, such as BACnet, for interoperability with a range of building automation systems.

In the context of the Technology and Products/Service Performance Gaps area, IPOS can potentially address the following technology and R&D gaps identified in the Roadmap:

Technology Gap 1 - Cheaper and simpler self-calibrating dimming controls: IPOS may be able to address this gap by optimizing parameters in the image processing algorithms to perform across a range of occupancy and lighting configurations. The IPOS technology is based on production-like embedded hardware and software along with mature open-source libraries. Estimates of occupancy including totals and location, coupled with intrinsic estimation of illuminance from the same sensor can provide a rich set of inputs to proof-of-concept algorithms that adapt lighting commands to the situation.

R&D Gap 1 - Cheaper and simpler self-calibrating dimming controls: Making daylighting cost effective continues to be a challenge. Cheaper, easier to use, and self-

calibrating controls can help to make daylighting more attractive and effective. IPOS can be used in conjunction with BAS algorithms to leverage the information needed to tailor lighting commands to the situation. The ability to detect occupancy, estimate occupancy location, and estimate space luminance from a singular sensor can potentially enable cost-effective and adaptive control for lighting or daylighting systems.

R&D Gap 2 - Human factor, usability, and comfort: Design standards behind healthy workplaces and control approaches to heating, cooling, lighting, and ventilation that increase occupant comfort and usability of spaces rely on robust and cost-effective sensing to provide data. IPOS has the potential to fundamentally improve occupancy sensing technology that is frequently used as a surrogate for these purposes. IPOS and associated control algorithms that leverage its outputs can substantially impact multiple aspects of occupant comfort and energy performance in a range of commercial building types including retail, office, healthcare, and education facilities.

FY 2011 DOE proof-of-concept prototype testing demonstrated that IPOS identified occupancy events better than two commercial passive infrared (PIR) sensors and was able to identify 96.6% of the occupancy events, compared to 70.4% and 76.9% for the two PIR sensors [6].

The BPA-funded project of FY 2012-13 enhanced the IPOS prototype to enable a richer set of sensor output data, and demonstrated control algorithms that leverage this new information to illustrate value proposition potential. The project objectives were to:

- Enhance the prototype and develop new algorithms to identify the number of occupants, activity levels, approximate positioning in a space, relative space illuminance, and dimming levels.
- Develop simple building EMS control algorithms for lighting and daylighting control.
- Sense occupancy and illuminance in multiple virtual zones using a single sensor.
- Test and document the performance of the prototype, to provide opportunities to identify areas of improvement of the technology.
- Perform applied testing to inform the commercialization phase.
- Evaluate the potential for IPOS used for daylight harvesting and dimming control through applied testing.
- Establish a licensing and commercialization path.
- Identify potential use cases and recommend next steps for future work.

Each project objective was met. The following sections and the appendices provide details on the activities and recommendations addressing project objectives.

2 Technology and Test Methods

2.1 Technology Overview

The IPOS prototype was extensively revised from the initial proof-of-concept implementation [6]. Most of the algorithms were rewritten and new demonstration algorithms were added to the prototype: illuminance assessment, dimming levels, activity level assessment, occupant count and location, and virtual zone controls through implementation of multiple regions of interest (ROIs). Figure 1 shows a prototype with enclosure; Figure 2 summarizes the main components and outputs generated by the prototype.



Figure 1: IPOS Sensor Prototype (NREL PIX 24421)

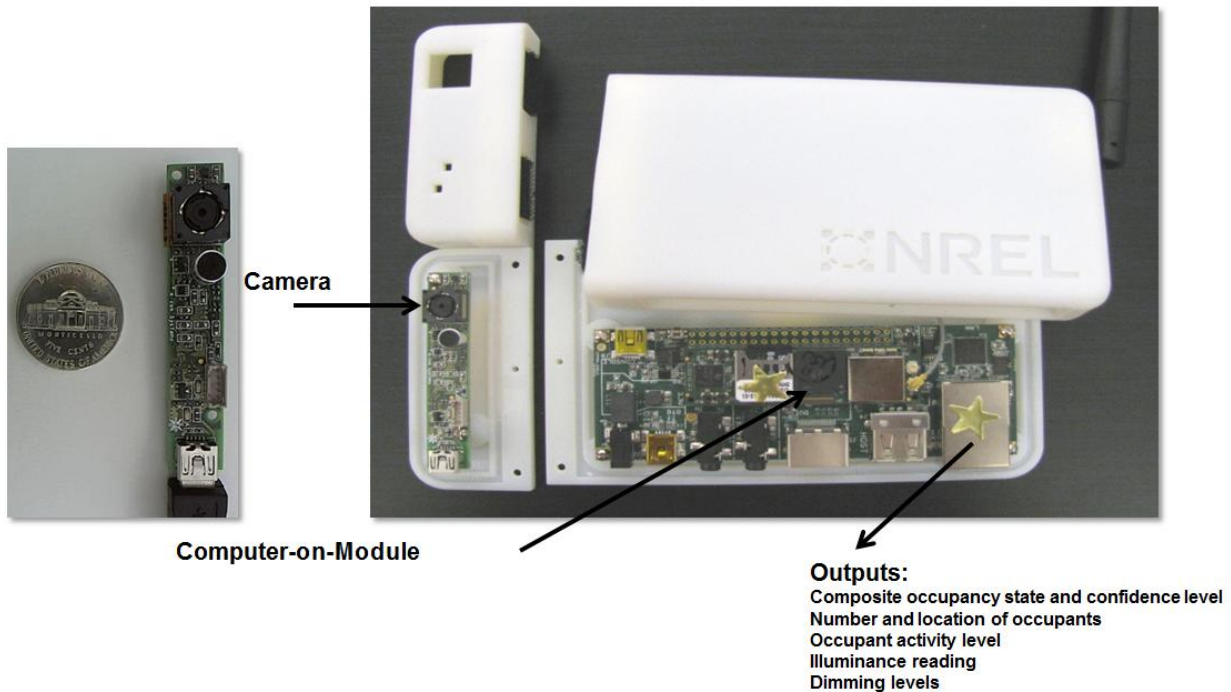


Figure 2: Main IPOS Components and Outputs (Luigi Gentile Polese/NREL)

The prototype includes the following software functionalities, each tasked with specialized responsibilities (Figure 3):

- Acquisition
- Detection
- Assessment
- Integration

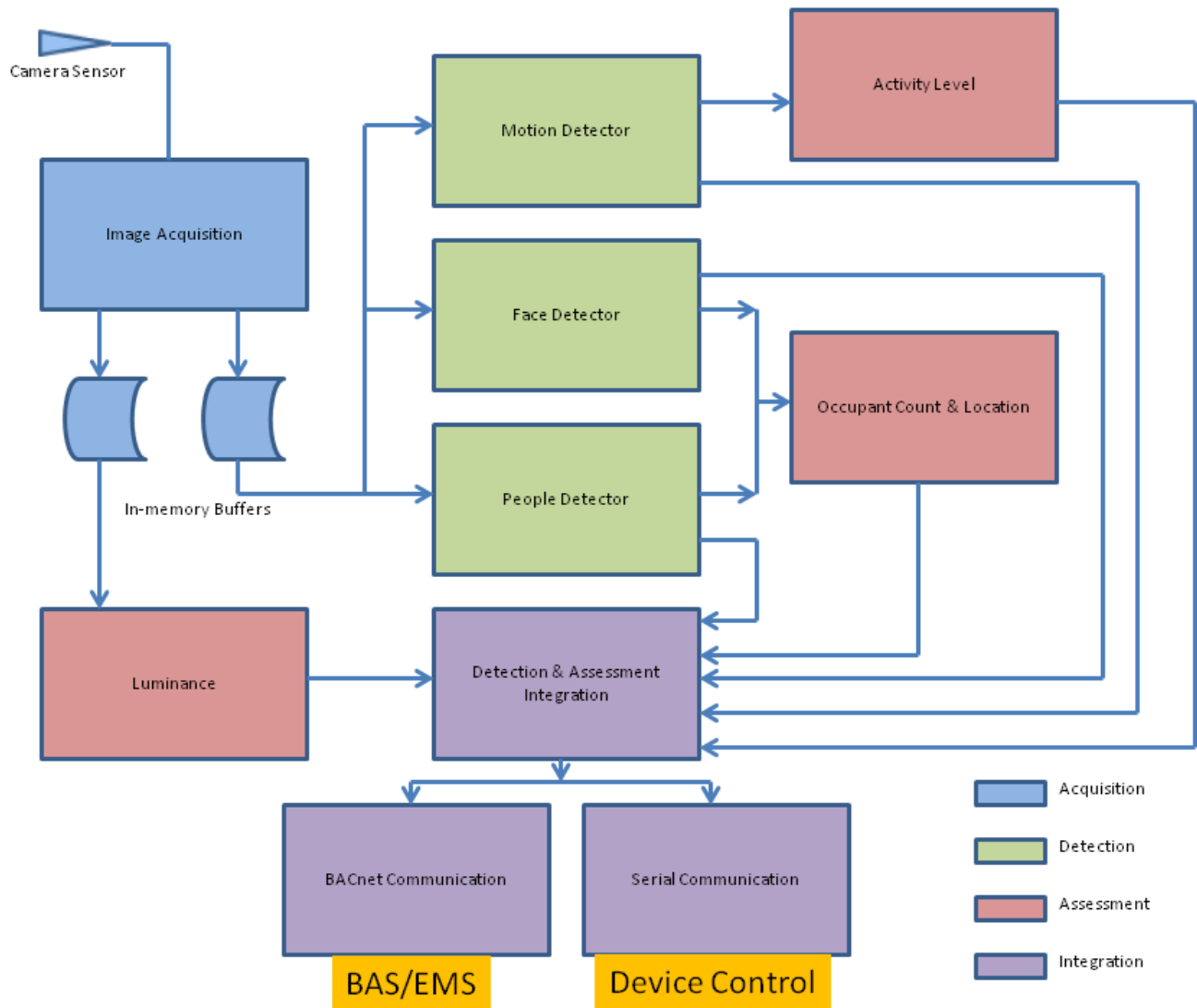


Figure 3: IPOS Software Architecture (Luigi Gentile Polese/NREL)

2.2 Detection Functions

The occupancy detection function of the IPOS prototype was the primary focus of the project. Functionally, the IPOS prototype is a demonstration of multiple sensing and assessment functions using open-source computer vision algorithms. The occupancy detection function is the result of the aggregation of a motion detection component and two motion-independent components. Each detection function is individually responsible for informing on occupancy state through a specific detection “component.” Each component is then integrated and assembled into a single composite occupancy signal (Occupied or Vacant) with an associated confidence level (see Section 2.6).

2.2.1 Motion

This detection function processes sequential frame captures to detect and report occupancy through motion analysis. Pixel-by-pixel image subtractions (Figure 4) are computed to eliminate the stationary elements in the frame (for example, walls, furniture, windows, fixtures, or equipment), which in the figure appear black. Moving areas are identified in the frames (in the form of moving area sizes and direction of motion – red circles in the picture) and their tracking is used to create a motion history element that is used to assess the number of independent areas moving in the scene, as well as individual and overall motion gradients. These elements are used to determine the extent of motion and a motion confidence level, which are then communicated to the sensor integration and activity level functions.



Figure 4: Motion Detection Evaluation Image (Larry Brackney/NREL)

2.2.2 Face

As for the motion detection function, the face detection function processes sequential frame captures to detect and report occupancy by identifying human face traits (Figure 5). The current prototype uses the Haar Cascade algorithm of the off-the-shelf, open source OpenCV library [7] with a general-purpose training set for the recognition of one or multiple frontal faces. Once detection occurs, the module performs additional

computations to determine face locations and relative sizes. An occupancy certainty (confidence) level is also computed. These elements are reported to the sensor integration and occupant location functions.



Figure 5: Face Detection Output Image (Luigi Gentile Polese/NREL)

2.2.3 People

This function, based on the OpenCV's implementation of the Histogram of Oriented Gradients (HOG) algorithm, processes individual frame captures to locate and identify the presence of whole-person traits to infer occupancy (Figure 6). As for the face detection function, the algorithm uses pre-defined generic training sets for the recognition of one or multiple persons in the scene. Once occupancy is detected, additional processing is performed to determine relative people position, size, and count. These elements, along with a confidence level estimate based on persistence of recognition over time, are communicated to the sensor integration and the occupant location functions.



Figure 6: People Detection Output Image (Luigi Gentile Polese/NREL)

2.3 *Assessment Functions*

We developed the assessment functions to inform the potential for new value propositions that leverage the rich set of outputs that can be generated from computer vision-based analysis.

2.3.1 **Illuminance**

This demonstration function analyzes specially-captured sensor images at a low frequency (for example, every 5 minutes) to assess average illuminance levels. The image frames are captured with the camera set temporarily with auto-exposure disabled. During analysis, the image capture is converted from red, green, blue format into individual Hue, Saturation, and Value (HSV) image components. Pixels of the Value image component are normalized to a scale range between 0 (black) to 255 (white). A simple average across all pixel values on the Value component for the entire image (and all ROIs) provides a digital reading. The more brightness in the image, the closer the average is to 255. Conversely, darker images would produce low digital readings. We collected several readings from the illuminance function along with readings from a light meter [10] calibrated and set to produce readings in Fc, and used the two data sets to calibrate the sensor through a polynomial regression equation. The coefficients of the equation are user-configurable through a file⁴. The function does not perform a reading of illuminance levels per se; rather, it produces a close approximation of illuminance readings under certain conditions and constraints. (See Appendix A.)

2.3.2 **Activity Levels**

This classification function demonstrates a basic assessment of occupant activity levels: sedentary and active. The output could feed into a building ventilation control algorithm, for example. The activity level is inferred from additional outputs not currently used for occupancy reporting, but internally generated by the motion detection function. The activity level is categorized as sedentary or active according to a comparison of motion components with a configurable threshold level.

2.3.3 **Occupant Count and Location**

This function demonstrates occupant counts and locations in the field of view, assuming that a hypothetical origin is located at the bottom of the image (Figure 7). The image, generated automatically when IPOS is configured in test mode, identifies the occupants' approximate locations, number of occupants, and approximate relative distances from the camera.

⁴ Re-calibration may be required if a different camera is used or if fixed-gain settings are changed.



Figure 7: Occupant Location Output Image (Luigi Gentile Polese/NREL)

The function leverages information generated by the face and people detection functions. In particular, geometry information about faces and people locations is further manipulated to obtain approximate occupant location in polar coordinates. Distance is estimated using the relative size of the occupants⁵. The output from this function can potentially feed into building HVAC or ventilation controls or it could be used for localized lighting controls.

2.3.4 Dimming Levels

The dimming function leverages the illuminance assessment algorithm and image segmentation (see below) for demonstrating daylight harvesting with the purpose of controlling light levels in a space. Illuminance values are compared to a pre-determined set of illuminance thresholds to determine a dimming level for daylighting applications. The IPOS prototype can be currently user-configured to produce a set of discrete dimming control levels; for example, 0% (no dimming – lights fully on), 25%, 50%, 75%, and 100% (fully dimmed – lights off). It can also be configured, through a user-configurable setting, for continuous dimming. The dimming level, calculated from the illuminance readings, is sent via BACnet or a serial connection to enable potential daylighting control applications; for example, the IPOS dimming value could be converted into a 0 to 10 Volt signal that in turn could be used to control ordinary dimming ballasts. In the prototype demonstration, dimming is dynamically updated for each ROI at the same user-defined frequency of the illuminance assessment function. (See Appendix B.)

2.4 Aggregation Functions

The outputs from the detection functions are aggregated to generate a single composite occupancy signal. Output from the assessment functions also are made available to the aggregation function. In the prototype demonstration, the complete set of outputs is then transmitted to a BAS via the BACnet protocol or a serial interface.

⁵ A more accurate estimate of distance and location would require two cameras, at the expense of higher hardware costs and software complexity.

2.4.1 Sensor Integration Function

This function collects and processes the data received from the detection and assessment functions. It processes the detection data streams to reach a composite occupancy/vacancy detection determination along with a composite confidence level, calculated using the individual detectors' confidence levels. The function then sends sets of occupancy signals to the BACnet communication function or the serial port, or both. The composite occupancy signal is evaluated from the individual occupancy signals received from the motion, face and people detection functions, along with cumulative occupancy data representing past occupancy signals over time. The cumulative occupancy variable is constantly re-evaluated according to elapsed time and reported occupancy levels.

The BACnet communication function implements the communication protocol between IPOS and the BACnet infrastructure. (See Appendix C for details on the IPOS-specific variables transmitted over BACnet.)

A serial communication function implementing the RS-232C protocol interface has also been developed. The outputs received from the sensor integration are transmitted via this interface to enable devices with a serial interface to potentially use IPOS outputs for direct actuation or control. The demonstration prototype currently sends the following outputs for the whole image and up to eight user-definable ROIs:

- Composite occupancy
- Composite confidence level
- Illuminance reading
- Dimming level
- Number of occupants
- ROI coordinates

2.5 *Image Segmentation*

Image segmentation is a functionality that partitions the images captured by the sensor into sub-regions for individual processing. Essentially, each detection and assessment function is available in pre-defined ROIs. Each ROI can be independently analyzed for motion, faces, and people. IPOS can then generate occupancy signals associated to each ROI. The ROI can also be processed for illuminance levels estimation, occupant activity level, and occupant count and position. For example, the IPOS image could be segmented into four pre-defined ROIs, each progressively more distant from the camera. This is in addition to whole-image processing, which also continues to be analyzed. The ROI concept is illustrated in Figure 8. The image is segmented into four progressively distant sub-perspectives, each representing a volume in the IPOS image. An occupant may be entirely contained in one ROI, or may span two or more ROIs.

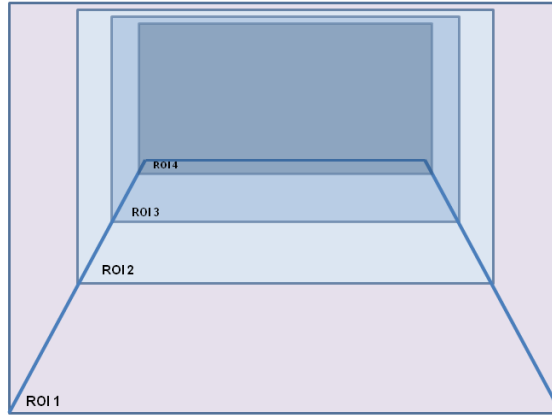


Figure 8: 3D IPOS ROI Concept

Translating the 3D ROIs in Figure 8 into 2D images as captured by the sensor camera, results in the image segments shown in Figure 9.

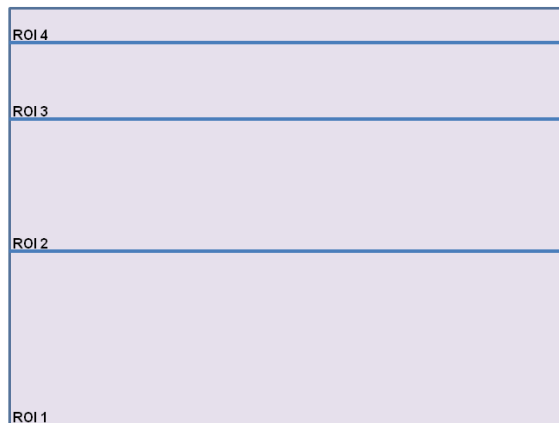


Figure 9: 2D IPOS ROI

Each ROI rectangle encloses a region of the image. Processing takes place for the whole frame (ROI 0) as well as for each ROI. However, the definition and processing of the ROIs put an additional computational burden on the embedded processor.

A user-configurable file, in conjunction with a visual aid of the image seen by the sensor camera, is provided for defining and configuring the ROIs through the display of a temporary grid superimposed on the image, also user-configurable (Figure 10).



Figure 10: ROI Configuration with Positioning Grid Overlay (Luigi Gentile Polese/NREL)

The grid size⁶, in pixels, is also user-configurable through an on/off setting for aiding in the precise positioning of the ROIs⁷. Up to eight ROIs can be user-defined through this process in the current demonstration, and up to 16 through internal software. In the current implementation, the ROIs can be rectangles defined only through sets of x, y coordinates anywhere in the image.

Once the ROIs are created and positioned according to needs, the user can instruct the prototype to no longer generate the grid overlay through the same on/off option, leaving only the ROI definitions in place. In a future development, this rudimentary configuration could be expanded to create an intuitive graphical user interface with drag-and-drop capabilities for easily creating and positioning ROIs of any shape. Such step would be essential during the commissioning phase of an IPOS-based sensor where multiple virtual control zones are desired.

2.6 Occupancy Signal and Confidence Level

The three detection functions generate periodic independent occupancy outputs and confidence levels. The periodicity is sensor-specific. The sensor integration function generates a composite occupancy and confidence level using previous state information, detector weighting factors, and current individual sensors' outputs through a proprietary algorithm. The purpose of the composite confidence level is to provide an indication of how certain the detector is about the occupancy/vacancy signal. Variables internal to each detector and the sensor integration function store their respective cumulative states representing how strong the detection has been so far. These states have a range from zero (no previous detection history) to a detector-specific maximum value. This state value increases as new detections are registered, and decays at each evaluation cycle if no new detections occurred. The evaluation cycle for the sensor integration function in the demonstration prototype was set to one second.

⁶ In the test image the grid is configured at 25 pixel spacing.

⁷ The images used in this project have a resolution of 640x480 pixels.

As detections occur over time, the detection history of each individual detector accrues. These detection history states influence the resulting occupancy and confidence levels. The current IPOS prototype generates occupancy signals when composite confidence levels are 70% or higher, switching to a vacancy signal when composite confidence levels fall below the same threshold (Table 1).

Occupied or Vacancy State	Occupied Confidence Level	Vacancy Confidence Level
Occupied	>70%	< 30%
Vacant	< 30%	>70%

Table 1: Confidence Level Thresholds

Each detector independently generates an occupancy signal and a confidence level. Faces or people may be detected with or without motion being detected; for example, an occupant walking in front of the camera sensor or an occupant standing motionless in front of the camera sensor.

Table 2 through Table 4 show examples of the composite occupancy signals and confidence levels (assuming no previous detection history) for strong and weak detection scenarios.

Detector	Occupancy State	Confidence Level	Detector Weighting Factor	Occupancy State Sent	Confidence Level Sent
Motion	Occupied	80%	40%	Occupied	80%
Face	Vacant	100%	30%		
People	Vacant	100%	30%		
Resulting Composite Occupancy Signal and Composite Confidence Level					

Table 2: Composite Occupancy and Confidence Level from Strong Motion Detection

Detector	Occupancy State	Confidence Level	Detector Weighting Factor	Occupancy State Sent	Confidence Level Sent
Motion	Vacant	65%	40%	Occupied	93%
Face	Occupied	93%	30%		
People	Vacant	100%	30%		
Resulting Composite Occupancy Signal and Composite Confidence Level					

Table 3: Composite Occupancy and Confidence Level from Weak Motion Detection and Strong Face Detection

Detector	Occupancy State,	Confidence Level	Detector Weighting Factor	Occupancy State Sent	Confidence Level Sent
Motion	Vacant	100%	40%		
Face	Occupied	90%	30%		
People	Occupied	75%	30%		
Resulting Composite Occupancy Signal and Composite Confidence Level				Occupied	83%

Table 4: Composite Occupancy and Confidence Level from Simultaneous Faces and People Detections

Figure 11 shows a simplified representation of the individual and composite occupancy signals and confidence levels. The figure shows that both motion and a face were detected at time=5, while a person (but no motion or a face) was detected between times 14 and 17. Weighting factors are used to calculate the composite confidence level at each sampling time. A real-time composite occupancy signal is generated when at least one detector is reporting occupancy and the composite confidence level is above the 70% threshold⁸. The composite occupancy and confidence levels in Figure 11 are further processed to eliminate sudden changes in the occupancy state before they are sent.

⁸ The confidence level threshold is configurable.

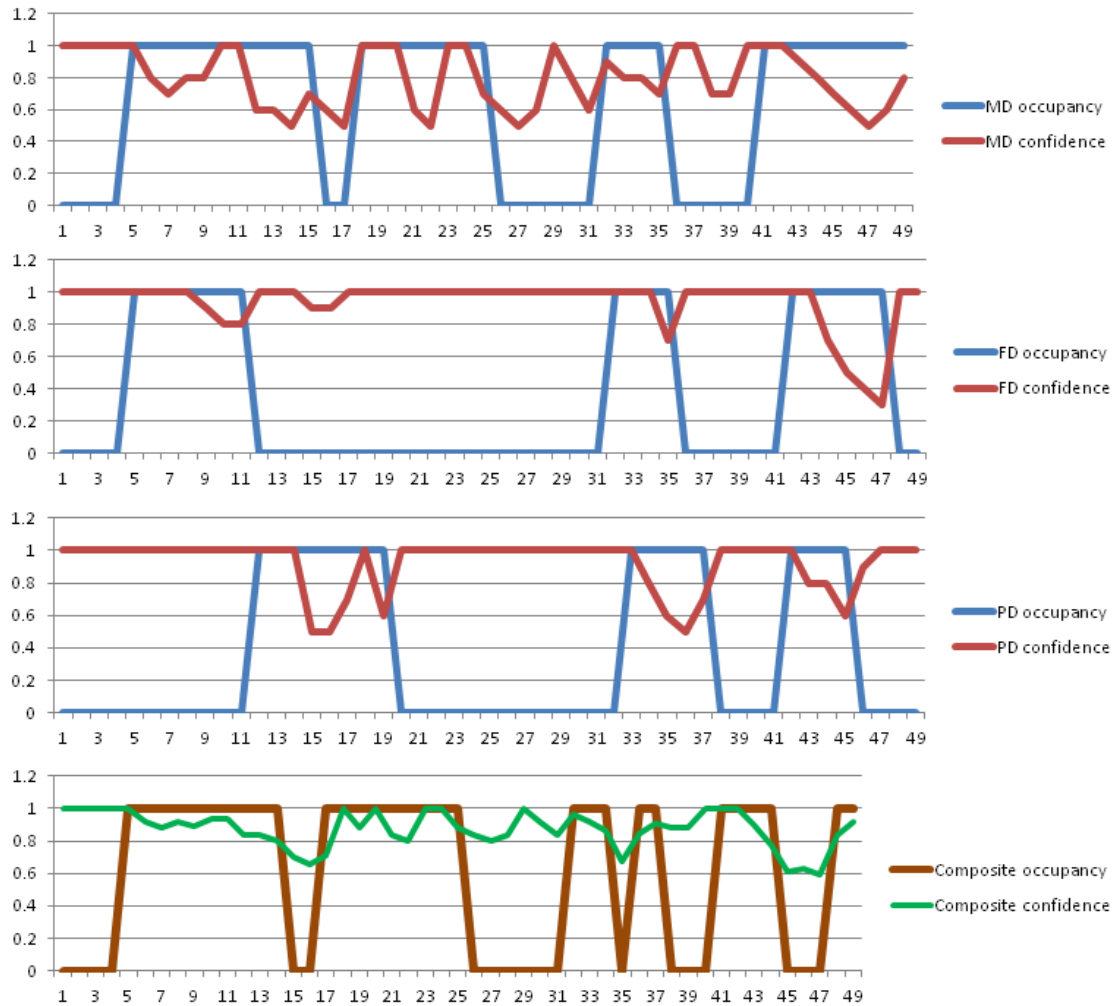


Figure 11: Composite Occupancy Signal and Confidence Level Determination

2.7 Adaptive and Equivalent Time Delay

IPOS does not use a fixed time delay to determine transition from last occupancy event to vacancy. The IPOS adaptive time delay considers the occupancy state and confidence level, cumulative states, and decay factors through a proprietary algorithm. In functional and applied testing the IPOS adaptive time delay was 3–5 minutes, which is shorter than typical PIR default time delays of 15–20 minutes.

2.8 Testing and Demonstration Activities

NREL worked with BPA to define and develop a test protocol and experimental design for functional and applied testing.

Unit and functional testing of the IPOS prototype was conducted in an NREL-controlled test environment; applied testing was conducted at a third-party location to assess potential evolution of the prototype for occupancy, daylight harvesting and dimming

control. (See Appendix D for more information on unit and functional testing.) Two use cases were demonstrated in a DoD office and at a large retail business.

Six IPOS prototypes were deployed at NREL's Research Support Facility (RSF) and occupancy was evaluated through log files. IPOS prototypes were configured to send occupancy and other feedback via BACnet to a portable prototyping EMS workstation demonstrating end-to-end communication and simple actuation of light-emitting diodes (LEDs) on the prototyping EMS workstation.

Table 5 summarizes the observed activities during the 19.25 hours of functional testing, broken down by the space use. (See Appendix D for a list of test scenarios.)

Activities under Test	Enclosed Office	Open Office Space	Conference Room	Kitchen	Print Room
Answering or Talking on the Phone	X	X	X		
Typing on the Computer	X	X			
Conversing with Another Occupant	X	X		X	
At a Wall Board: Writing, Talking, and Erasing	X		X		
Individual Activity at Desk (Writing, Eating, Etc.)	X	X			
Staying Still, Either Standing or Sitting	X	X			
Walking In/Out	X			X	X
Space Vacant, Computer Screen On	X	X			
Various Activities (at Desk, Some Walking or Standing)		X			
Space Vacant	X	X	X	X	X

Table 5: Functional Testing Conditions and Spaces

The images were compared to IPOS outputs to evaluate the functional test results. Figure 12 shows a sample functional evaluation session, with (clockwise from top left) image outputs from the motion and people detectors, composite output log from the debugger, and image outputs from the face detector and illuminance assessment function.

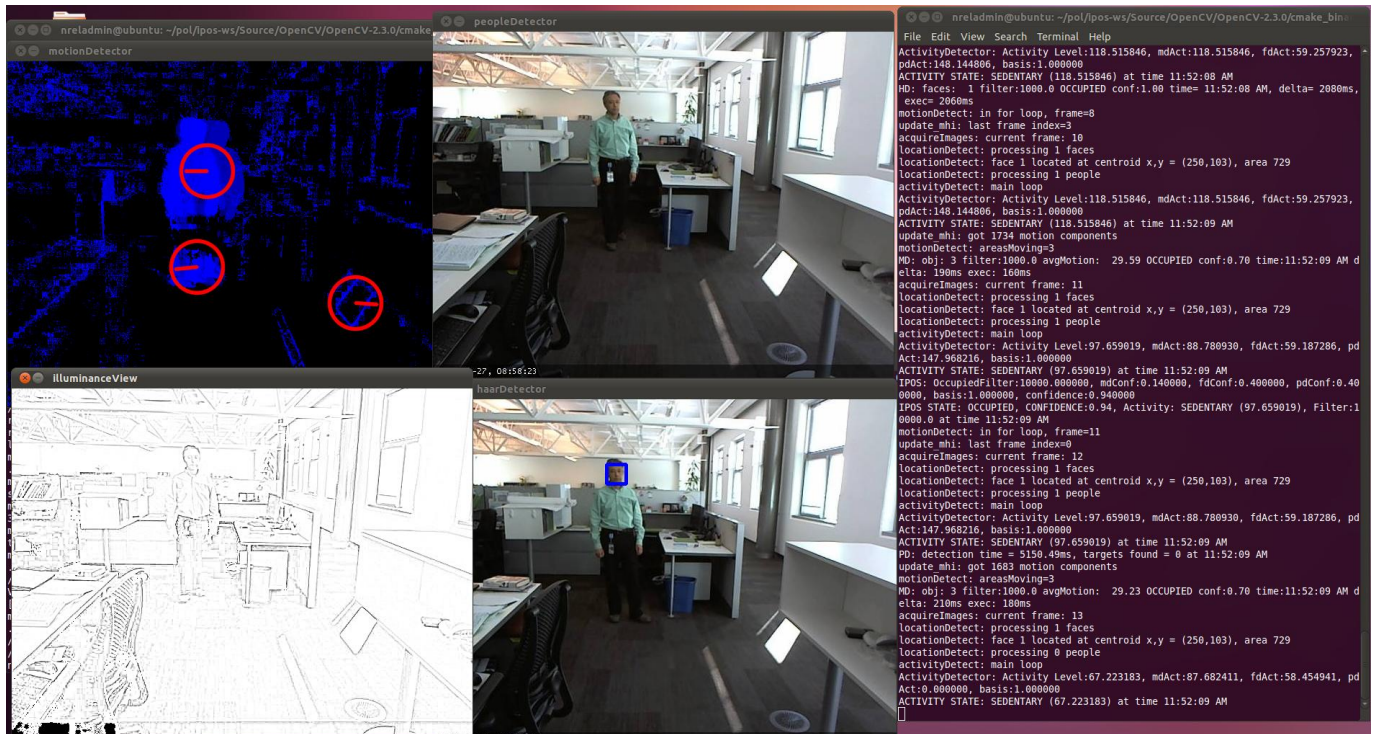


Figure 12: IPOS Test Session Output (Clockwise from Top Left: Motion Detector, People Detector, Composite Output Log, Face Detector, and Illuminance) (Luigi Gentile Polese/NREL)

2.8.1 Live Prototype Test

Six prototypes were installed at NREL's RSF. Occupancy state was reported via the prototypes' log files. The prototypes did not control any lighting loads; rather, they were monitored remotely for downloading occupancy logs and runtime information to evaluate performance.

Accuracy of the data generated by the IPOS sensors during the live test was validated through spot-checking occupancy status, using images saved for this purpose. This validation activity was performed for two reasons:

- To verify that the accuracy remained substantially the same as found during functional testing.
- To collect and use the "raw" occupancy images as a theoretical limit for actual occupancy and vacancy periods, for comparing IPOS and traditional occupancy sensor performance and energy savings potential.

During the test period, IPOS was configured to save the most recent images for troubleshooting and debugging purposes. Figure 13 shows one of the saved images with sensor output information superimposed to the image. Future versions of the prototype will not be able to store images due to privacy considerations.



Figure 13: IPOS Composite Status Image (Luigi Gentile Polese/NREL)

The large circle represents the occupancy state (occupied), along with the states reported by the following modules: motion detection (MDM), face detection (FDM), people detection (PDM), and activity detection (ADM). The numbers by each detector indicate the number of objects being detected. In the case of the MDM, the number 1 implies that one independently moving area in the frame was identified⁹. No faces or people were reported for this image, because the face recognition algorithm was using generic training sets for detection of frontal faces; similarly, the people recognition algorithm is trained to detect standing people.

2.8.2 BACnet Functional Testing

During functional testing, the IPOS prototype sent the following outputs over BACnet:

- Occupancy
- Confidence level
- Activity level
- Estimated Illuminance
- Dimming level
- Number of occupants
- ROI coordinates

The outputs were generated for the entire field of view (ROI 0) and up to eight user-defined ROIs (ROI 1 through 8). The NREL RSF was not equipped with a BACnet Gateway for IPOS connection; therefore, functional testing was conducted using a portable EMS workstation with a BACnet Gateway.

The workstation had a range of hardware and software equipment for commercial building automation applications. These include HVAC, lighting control, building access, and building security offerings. The Open, Real-Time, Control Architecture (ORCA)

⁹ This number does not necessarily map to number of occupants.

hardware and software product line is widely used at NREL, because of the flexibility of the General Control Language (GCL+) and because of its compatibility with BACnet.



Figure 14: Portable EMS System (Larry Brackney/NREL)

Figure 14 shows the portable EMS workstation used for BACnet functional testing. During IPOS functional testing three IPOS prototypes were networked to the portable EMS workstation using BACnet over 100BASE-T Ethernet. The first hop of the Ethernet connection to the IPOS devices was through a dedicated wireless subnet.

A simple control algorithm programmed using the GCL+ language from the operator workstation (OWS) reading IPOS BACnet occupancy values allowed physical actuation of LEDs on the portable EMS workstation in response to the occupancy signals generated by the IPOS prototypes.

2.8.3 Applied Testing

An IPOS prototype is currently deployed at a third-party location for collecting feedback on a potential daylighting harvesting and control application. When completed, the results of applied testing are expected to inform on potential to evolve IPOS into a new combined daylight harvester and occupancy sensor.

The IPOS prototype is configured as a combined occupancy sensor, daylight harvester, and dimming controller of two lighting zones. The occupancy and dimming outputs generated by IPOS are utilized to control the lighting power levels of a conference room. (See Appendix H (Daylight Harvesting and Occupancy Control section) for a description of the applied testing demonstration setup.)

3 Functional Test Findings

3.1 Mounting Locations

The IPOS prototypes used a camera with a 45° field of view. Its mounting location presented unique challenges. Commissioning traditional occupancy sensors is difficult; however, one advantage of the IPOS sensor placement was that the coverage area could be visually inspected with great accuracy through a monitor connected to the IPOS prototype camera.

We learned that the mounting location of the IPOS prototype directly affected performance and usability. The following are preliminary observations and recommendations:

- Avoid placing the sensor where the field of view includes areas subject to sudden lighting level changes and bright lights. Examples include large areas receiving direct natural light or light fixtures. Sudden light brightness changes (for example, due to rapid cloud movement or lights being turned on) were observed to cause the motion detection function to report false positives. Slowly changing light levels¹⁰—direct, indirect, or reflected—did not affect IPOS performance.
- The maximum range of the camera in the RSF open office space was approximately 100 feet. However, occupancy was verified only at a maximum of approximately 40 feet, because the default training data sets for people and face detection employed did not include distant subjects. There is potential, however, for occupancy detection in ROIs covering distant areas of the field of view in combination with training data sets that include distant subjects and with region-specific sensitivity threshold settings.
- Avoid placing the sensor so the field of view includes large glass surfaces (for example, glass doors, windows, glass enclosures) or other reflective material, because glare or reflections can induce false positives and yield incorrect lumen readings.
- To reduce the number of sensors in large open areas and ensure uniform coverage, cameras with a field of view larger than 45° could be employed. However, we did not test the prototype with other fields of view to assess occupancy detection performance.
- Unless only motion (not occupancy) detection or illuminance/dimming level outputs are desired, ceiling mounts should be avoided (see next item).
- Avoid mounting locations higher than 10 feet or lower than 6 feet from the floor, as the high and low occupant perspectives can negatively impact face and people detection. If high mounting locations are desired (for better coverage or for practical reasons), specific training data sets would need to be developed for face and people detection.

¹⁰ Compared to the motion sensing evaluation cycle of 3-5 seconds.

- The sensor did not need to be exactly horizontal; in some cases, non-level placement can be used intentionally to exclude areas from the sensor's field of view (light fixtures, for example). However, excessive misalignments with the vertical (estimated at greater than 15°) can reduce the detection success rate of the face and people detectors.
- Like PIR motion detectors, the IPOS prototype needs to be in line-of-sight with the occupants for detection to occur.
- The direction of occupant movement relative to the IPOS camera did not significantly affect performance. Occupants moving along the field of view (directed toward or away from the IPOS camera) had a positive impact on the face and people detection rate; occupants moving across the field of view could better detect motion and classify activity levels.

3.2 *Detection Accuracy*

Accuracy was evaluated during functional testing by comparing known image sets against the output logs. Occupancy and vacancy output signals were recorded in log files at 1-second intervals (for a 19.25-hour total test period) and compared with the image sets. The IPOS occupancy signal was determined to be 99.6% accurate (Table 6). This is significantly higher occupancy detection accuracy than the two PIR sensors tested in an earlier study [6], which were determined to be 70.4% and 76.9% accurate. The vacancy signal was 98.5% accurate. Functional testing also found false events (both false positives and false negatives), which prompted algorithm changes to minimize these occurrences. (See Appendix G for a discussion on findings and technology improvement recommendations regarding the image acquisition function and individual detector and assessment functions accuracy.)

Occupancy Accuracy	Vacancy Accuracy	Average Accuracy
99.6%	98.5%	99.0%

Table 6: IPOS Detection Accuracy

3.3 *Applied Testing*

During applied testing at a third-party location, the IPOS prototype was connected to a lighting dimming system (see Appendix H (Daylight Harvesting and Occupancy Control section) for a description of the applied testing setup), and the occupants reported that the light levels appeared to change with no apparent reason, creating distractions and the perception of a lighting system problem.

A simple new dimming control demonstration algorithm was implemented and tested at the same location. As described in Appendix B, the new algorithm provided an acceptable solution to the occupant perception. See Section 5.2 for a description of preliminary observations from applied testing activities.

3.4 Calibration Considerations

The IPOS prototype has a complex set of configuration parameters that have the potential for a high degree of flexibility in various applications and environments. However, it also has the potential to add complexity to future calibration and commissioning activities. The solution used by the IPOS prototype was to expose key configuration parameters through a user-modifiable file interface. The following sections highlight our experiences during calibration of the prototype.

3.4.1 Motion Detection Function

The motion detection function has to be calibrated to minimize the potential for false positives and maintain enough sensitivity to detect small movements from occupants (for example, from computer work) or to detect occupants far from the camera. The main lessons learned during calibration were related to false positives caused by lighting condition changes and exposure control settings of the camera.

Figure 15-Figure 16 are images generated by the motion detection function for a room receiving natural light, with electric lights off and at a time of day when natural light levels are relatively low, in the range of 5-10 Fc.

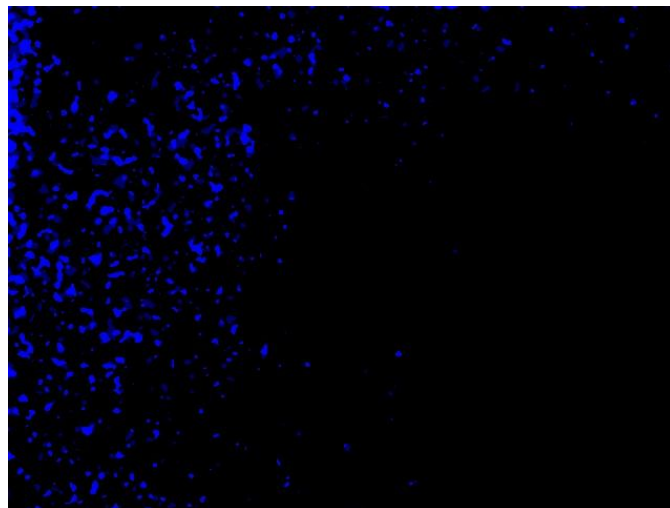


Figure 15: Motion Detector Output under Low Light (Luigi Gentile Polese/NREL)

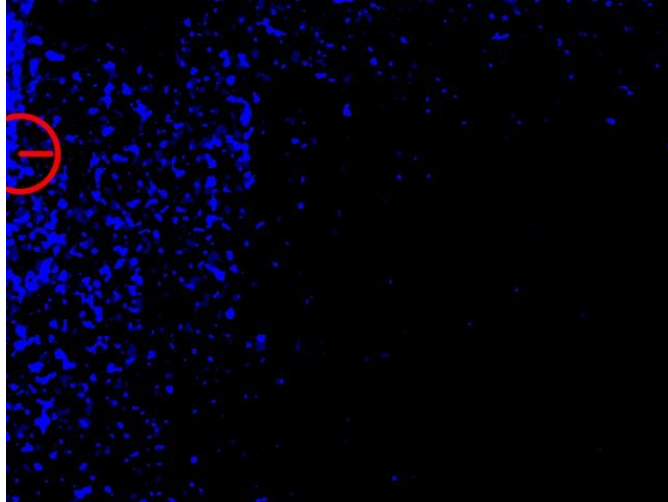


Figure 16: Motion Detector Output under Low Light (One Area in Apparent Motion)
(Luigi Gentile Polese/NREL)

In these low light conditions the auto-exposure settings of the camera are typically set to a high gain to compensate for the low light levels entering through the lens. These high gain settings typically produce low-contrast, over-exposed images. When image subtraction is performed by the motion detection function, noise patterns like the ones in Figure 15 induce the detection algorithm to report small average motions, either with areas identified as moving (one area in Figure 16, represented by the red circle and radius indicating direction of apparent motion), or motion without an identified area (Figure 15). Typically, these situations can be mitigated with a threshold setting in the motion detector for the average motion. We determined this calibration threshold experimentally; however, it is our experience that the setting is specific to the location in which the sensor is installed, and may need to be seasonally adjusted, which prompts for the need of a future automated motion-sensing calibration process.

Sudden changes of lighting conditions typically are picked up by the motion detection function as one or a few large moving areas. Figure 17 shows an example image output.

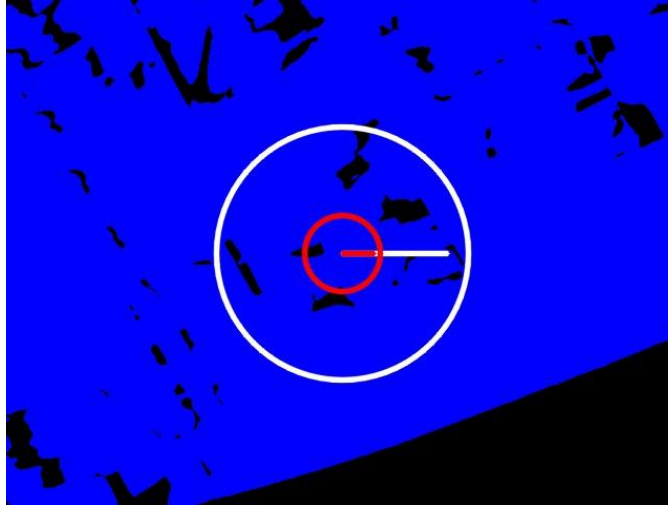


Figure 17: Motion Detector Output of Sudden Lighting Change (Luigi Gentile Polese/NREL)

We developed a calibration parameter based on relative illuminance changes between frames and used a threshold level when evaluating apparent motion. A new motion associated with illuminance variations exceeding the threshold level is considered a false positive and is not reported to the sensor integration function. The same considerations apply to the need for an automated calibration process for this parameter.

3.4.2 Face and People Detection Function

The only calibrations needed for the face and people detection functions were to determine respective thresholds for when the detector should report presence, and a time value used to determine for how long recognition should be used as past history of detection. These calibration parameter choices seem to be independent of space type or environmental conditions, and do not require specific calibration during the commissioning phase.

3.4.3 Illuminance Estimation Function

As the sample illuminance function calibration procedure shows (Appendix A), the camera sensor exhibited a limited, non-linear dynamic range. The non-linearity was corrected through a second-order function transformation. With our fixed-gain sensor settings, the IPOS prototype was able to assess illuminance readings in the range 24.5-44.4 Fc with a maximum error of 1.48 Fc. The settings used in the demonstration suggest that it is possible to obtain a fairly accurate estimate of the illuminance levels, provided that the illuminance range is about 20 Fc.

However, other space types or space uses typically exhibit different illuminance ranges, requiring the estimation function to respond to different ranges with acceptable accuracy. Assuming that the illuminance range does not vary significantly from the one tested, IPOS could be calibrated for different illuminance ranges by modifying the fixed gain value setting in the image acquisition function, and by having the illuminance function use a different illuminance transformation function. The latter is specific to the

new range of illuminance levels. This process has the potential for application to other space types and uses and for automatic configuration (calibration) through a simple user interface presented to the user during the commissioning phase. The interface would consist of a limited set of questions about the space in which the sensor is being commissioned, space type and use, and whether windows or other sources of natural light are present in the commissioned area. The answers to these simple questions would guide the IPOS software to determine the most appropriate (and probable) settings needed to estimate illuminance, without requiring the use of a light meter for calibration during commissioning.

3.5 *Energy Savings Considerations*

A preliminary energy savings assessment was done by examining vacancy periods reported by the prototype, and comparing them against those reported by a generic PIR occupancy sensor model with varying time delay settings. Generally, occupancy sensor energy savings depend on multiple factors, which are often interdependent:

- Load controlled by the occupancy sensor
- Occupancy patterns
- Space type and use
- Level of “occupant ownership” of the space (shared or occupied by the same occupants - one or more habitual occupants)
- Daylighting patterns
- Time delay and sensitivity settings

Occupancy sensors are best utilized where occupancy is intermittent and unscheduled. Occupancy sensors should maximize energy savings without affecting occupant satisfaction (i.e., the energy savings should be obtained without interfering with the occupants’ daily activities). Because some degree of uncertainty is always associated with occupancy determination, traditional occupancy sensors utilize time delays and sensitivity settings as common measures to compensate for these uncertainties [11]. However, these mitigation measures have a direct impact on energy savings. A time delay of 15-30 minutes could prevent lights from being turned off unexpectedly while the area is still occupied and mitigate user dissatisfaction, but it will also reduce energy savings potential over the life of the sensor. A higher sensitivity setting can also affect energy savings by falsely detecting occupancy and turning on lights during unoccupied periods.

The IPOS prototype used an adaptive time delay of 3-5 minutes between the end of occupancy and the IPOS vacancy signal. However, no actual lighting control was in place, so we do not have occupant feedback on the adaptive time delay.

We used raw occupancy logs generated by the IPOS prototypes to determine actual unoccupied and occupied periods. The raw logs contained data points representing the

instantaneous occupancy signal (occupied=1, vacant=0) taken at 1-second intervals, to accurately capture the beginning and end of each occupied period in the field of view. We were comparing the performance of the prototype and traditional occupancy sensor models, so the energy savings were not directly calculated; rather, only vacancy percentages were calculated.

When calculating occupancy sensor energy savings, lighting loads are assumed to be on continuously during occupied periods. With this baseline assumption, typical energy saving estimates for traditional occupancy sensors range between 17 and 60% across a variety of space types [12]. For any given space, the main factors affecting occupancy sensor performance are accuracy and time delay. “Smart” occupancy sensors employ time delays that adapt to occupancy pattern variations, which may provide better performance and energy savings than traditional occupancy sensors. In one published study [13], smart sensors exhibited 5% more energy savings than traditional occupancy sensors.

As one of the first smart sensors, IPOS uses an adaptive time delay that is dynamically calculated based on a cumulative variable representing past occupancy history.

For comparing IPOS and traditional occupancy sensor performance, the sensor accuracy was assumed to be equal, resulting in a conservative comparison. The following steps were performed for informing potential energy savings comparison:

1. Collect IPOS raw occupancy data and logs.
2. Partition the data into three periods of interest: weekdays, nights, and weekends.
3. Use the raw occupancy data to develop a model for calculating traditional occupancy sensor vacancy times at multiple time delay settings for a generic PIR sensor.
4. Calculate the occupancy sensor vacancy times at time delay settings of 5, 10, 15, and 20 minutes for the PIR sensor model.
5. Use the actual IPOS occupancy logs to calculate the IPOS sensor vacancy times.
6. Compile the results.

The IPOS vacancy percentages were calculated as follows:

1. Record total time duration of the log, T_{total} .
2. Identify vacancy and occupancy periods and record individual durations, T_{vi} and T_{oi} , respectively.
3. Sum all vacancy periods, $T_{vtot} = \sum T_{vi}$. Note that the total vacancy period is the time for which the sensor (IPOS or traditional) would have sent an unoccupied, or off signal to the controlled loads.

4. Sum all occupancy periods, $T_{Otot} = \sum T_{Oj}$. This value is the time for which the sensor (IPOS or traditional) would have sent an occupied, or on signal to the controlled loads. Note that $T_{Vtot} + T_{Otot} = T_{total}$.
5. Calculate the vacancy percentage as $E_s = 100 * T_{Vtot}/T_{total}$.

The same procedure was used to calculate traditional occupancy sensor vacancy percentages, but with vacancy times modeled according to varying time delays. Finally, the instantaneous occupancy logs (i.e., the raw log files) were used to calculate the actual vacancy times and percentages.

3.5.1 Periods of Interest

Assuming equal accuracies, the only remaining variable affecting sensor performance is the time delay between actual vacancy and the sensor vacancy signal. From the occupancy logs it was determined that weekdays between 21:00 and 06:00, and weekends between 19:00 and 07:00 were consistently vacant periods. For this reason these periods were not analyzed because the sensor performance would be practically the same. The remaining periods of interest are listed in Table 7.

When	Period	Times From	Times To	Comments
Weekdays	Regular Work Hours	06:00	18:00	Core hours of occupant activities
Weekdays	Cleaning Sshift	18:00	21:00	Occupants typically have left, cleaning crews may be present
Weekends¹	Day	07:00	19:00	Typically unoccupied, some daylight
¹ – includes holidays				

Table 7: Periods of Interest for Sensor Comparison

Close examination of the occupancy logs determined that lighting levels were sufficient for IPOS to detect occupancy events if they occurred.

The collected data was partitioned into each period of interest for processing and analysis.

Raw logs were used as input data for the traditional motion sensor model. The model generated occupancy data, assuming same accuracy as IPOS, for time delay settings of 5, 10, 15, and 20 minutes.

Both the PIR occupancy logs generated by the models and the IPOS logs were processed to determine potential energy savings through vacancy percentages. Appendix E includes vacancy percentages for each period of interest and each sensor.

3.6 Sensor Comparison

IPOS exhibited better performance than the model of traditional occupancy sensor because the adaptive time delay was consistently shorter than the fixed time delay settings. Using as PIR comparison the typical time delay setting of 15 minutes, the total

IPOS vacancy time was 25.7% more than the traditional PIR occupancy sensor model during core weekday hours, and 26.2% and 32.3% more during weekday nights and weekends, respectively (Appendix E).

We also used the raw occupancy logs to determine theoretical best – the vacancy percentages assuming perfect occupancy knowledge. Figure 18 shows a comparison of energy savings percentages for perfect occupancy knowledge, IPOS and PIR sensor models with typical time delay settings.

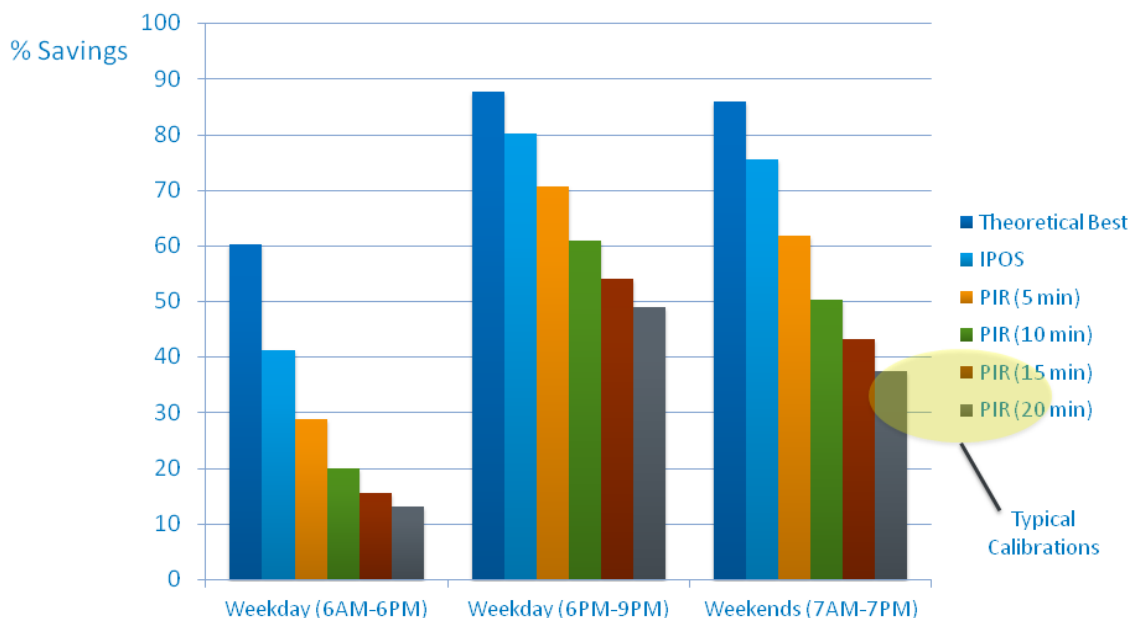


Figure 18: Energy Saving Comparisons for IPOS, PIR, and Theoretical Best (Larry Brackney/NREL)

Comparing IPOS and the PIR model with a time delay setting of 15 minutes against the limit theoretically obtainable, the PIR sensor model achieved close to half of the maximum vacancy percentage obtainable, while IPOS exhibited a 36% improvement, over the PIR sensor, toward reaching that limit.

4 Commercialization and Technology Transfer Efforts

In alignment with research and project goals, significant efforts are underway to support and facilitate a path to licensing and commercialization, and to collaborate with companies to advance research and bring the technology to market. Although IPOS is not currently licensed to be part of a commercially available product, licensing efforts will continue. Additional IPOS research is highlighted in the following sections.

The IPOS research generated two patent applications, which were filed with the U.S. Patent and Trademark Office [15-16]. In addition, IPOS was the recipient of the prestigious 2013 R&D 100 Award¹¹.

Requirements gathered through interviews with manufacturers of sensors and controls indicated two basic needs of new occupancy sensing technology:

- The cost of the hardware needs to be at the lowest level possible, to the point it can be considered a commodity.
- How proven is the technology? Are there case studies or demonstrations of the technology?

The IPOS technology makes use of commodity hardware that is available from the smart phone industry. Further streamlining and customization of the hardware is possible, although it is outside the scope of this project. We are addressing the second need by developing several prototype demonstrations¹² of other IPOS use cases.

4.1 Commercialization and Technology Transfer

The IPOS project partnered with NREL's Commercialization and Technology Transfer division, whose mission is to accelerate the commercialization of NREL-developed technologies and products under the protection of either nonexclusive or exclusive rights through several key activities, including technology partnership agreements, innovation management, and licensing.

Most NREL licenses are royalty-bearing and nonexclusive, and contain annual performance milestones; however, NREL may grant an exclusive license when such a license is the best mechanism for maximizing a technology's market impact¹³. For IPOS, NREL Technology Transfer and Commercialization is devising a strategy of multiple nonexclusive licensing scheme of the technology to broaden influence, maximize taxpayer investment, and at the same time reduce risks.

Regardless of the licensing scheme, the licensing agreement process (of which IPOS is part) basically includes seven steps¹⁴ (Figure 19):

¹¹ <http://www.rdmag.com/news/2013/07/2013-r-d-100-awards-winners-announced>

¹² See Section 5 for details.

¹³ www.nrel.gov/technologytransfer/licensing_agreements.html

¹⁴ The following section text is also available at www.nrel.gov/technologytransfer/licensing_agreements.html

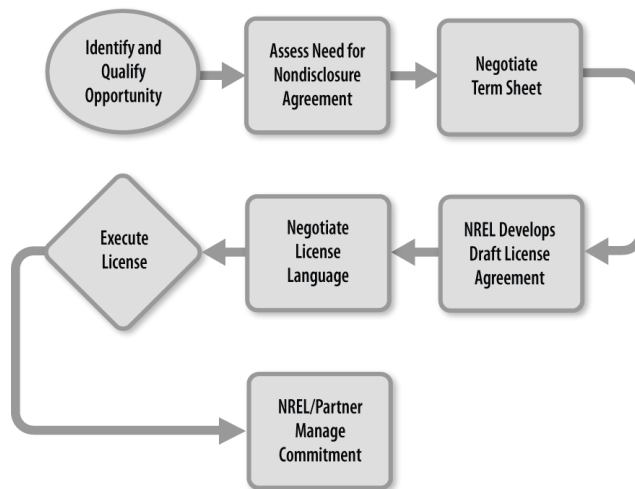


Figure 19: Licensing agreement flowchart (source: NREL)

1. **Identify and qualify opportunity:** To identify an opportunity, a company can browse the technologies available for licensing. When an opportunity has been identified, NREL then asks the company to provide information to assess its resources, capabilities, and commitment to commercialize the technology. Forms and questionnaires are available on the web (link above). The company must provide this information, so NREL can evaluate whether a licensing agreement would be beneficial for both the lab and the company. If the licensing opportunity meets these qualifications, we ask the potential licensee to review our mandatory license clauses to see if they're acceptable before investing time in the development of a license. If the company finds them acceptable, negotiations may begin.
2. **Assess need for a nondisclosure agreement:** At the beginning of the negotiation process, NREL and the company will assess whether they need a nondisclosure agreement.
3. **Negotiate terms sheet:** The next step involves negotiating the business terms of the license, such as field of use, the intellectual property that is being licensed, fees, royalties, milestones, and restrictions.
4. **Develop draft license agreement:** After the company and NREL agree on the terms sheet, NREL will draft a license agreement. NREL's licenses include language on fees, grant of rights, nonexclusive or exclusive terms, regulatory approvals, limited warranty, and indemnification.
5. **Negotiate license language:** The company then reviews and comments on the license agreement draft. If needed, the company and NREL negotiate the license's language. Many aspects of NREL licenses are negotiable, but some are not. Nonnegotiable items include those required under our operating contract with the U.S. Department of Energy. We're also sometimes limited on our flexibility with other items.

6. Execute license: When the negotiation process ends, NREL and the company execute the license under the terms of the agreement.
7. Manage commitment: Both NREL and the company manage their performance milestones for achieving the license's commercialization goal.

4.2 Energy Innovation Portal

IPOS was featured in 2012 on the DOE Innovation Portal¹⁵, where promising new technologies ready for licensing and commercialization from national laboratories are showcased to industry and manufacturers.

The portal is designed to be a central hub for investors, entrepreneurs, and businesses to access energy efficiency and renewable energy innovations. Its primary focus is on technologies in the energy efficiency and renewable energy market space. The site highlights licensable technologies through marketing summaries. These summaries break down the market opportunity of each technology by featuring a user-friendly description, explanation of the benefits, and applications for the technology. The Portal also contains more than 15,000 issued U.S. patents and published U.S. patent applications created with U.S. Department of Energy funding. These patents span the entire spectrum of DOE research, from nuclear energy to fossil energy to biotechnology.

A webinar presentation of the IPOS technology was held in 2013 on the DOE Innovation Portal, showcasing promising technologies ready for licensing and commercialization from the US DOE National Laboratories.

4.3 Colorado Center for Renewable Energy Economic Development

The Colorado Center for Renewable Energy Economic Development¹⁶ (CREED – formerly known as Colorado Cleantech Initiative) brings together stakeholders and service providers that support the creation and growth of startup cleantech companies, acting as a catalyst for economic development in Colorado. CREED is a partnership between the state and NREL and is located in Golden, Colorado. CREED provides facilities and programs for the clean energy/cleantech ecosystem. Monthly meetings provide opportunities for networking between entrepreneurs, investors, local service providers, and for entrepreneurs to practice pitching their business cases in front of investors. Key industry topics are covered in special presentations. Meetings are held at various locations, including the CREED offices in Golden, the Denver Chamber of Commerce building in downtown Denver, and periodic visits to other areas of the state.

As part of the monthly activities, the IPOS project delivered a webinar on the technology in 2012 to several participating companies and had follow-up conversations with startup cleantech companies interested in IPOS and new potential applications.

¹⁵ See www.techportal.eere.energy.gov

¹⁶ See www.creed.org

4.4 Industry Growth Forum

NREL's Industry Growth Forum¹⁷ is the nation's premier annual event for emerging clean energy and energy efficiency technology startups to gain exposure to and feedback from venture capitalists, corporate investors, government agencies, and strategic partners. The IPOS project was present at the forum with a demonstration booth.

The Forum features presentations from more than 30 emerging clean energy companies, provocative panels led by thought leaders, facilitated one-on-one meetings, and technology accelerator workshops. It is the perfect venue for growing companies to prepare, refine, and present their business to a wide range of stakeholders. Collectively, as of 2012, companies who have presented at the Forum since 2003 have raised more than \$3.4 billion in growth financing.

4.5 Research-Sharing Initiatives

4.5.1 Conduit/E3T Northwest

The BPA Energy Efficiency Emerging Technology (E3T) program is an ongoing collaborative effort involving BPA, Washington State University Energy Program, Northwest Energy Efficiency Alliance, and national experts to identify, assess, and disseminate innovative, highly-valued energy efficiency strategies and technologies that promise significant region-wide energy savings.

A webinar¹⁸ on the IPOS research was jointly presented with BPA in 2012. This research-sharing initiative is part of a series of webinars, sponsored by the BPA with support from the Western Area Power Administration.

4.5.2 Conference on Building Energy and Environment

A paper on IPOS research [14] was presented at the Second International Conference on Building Energy and Environment (COBEE) in 2012.

4.5.3 Intelligent Building Operations

IPOS research was presented at the Intelligent Building Operations (IBO) workshop in 2013.

¹⁷ See www.industrygrowthforum.org

¹⁸ <https://conduitnw.org/Pages/Event.aspx?RID=700>

5 Conclusions and Recommendations

Because of the diverse outputs that IPOS can generate, several potential use case opportunities have been identified for future developments. The following sections describe potential IPOS use cases and, for some, early testing demonstration efforts¹⁹. Recommendations for future developments, both short and long term, are also included.

5.1 *Daylight Harvesting Commissioning Tool*

5.1.1 Opportunity

A use case could include IPOS being used as a temporary daylighting and occupancy sensor commissioning tool, or as a permanent photosensor and continuous commissioning tool. Daylighting control is a necessary feature in most buildings seeking aggressive energy performance. Codes and standards such as ASHRAE 90.1-2010 and California Title 24 are starting to ensure this through prescriptive measures such as a sidelit and toplit space daylighting control requirement and daylighting system commissioning clauses. Energy performance disclosure laws and net-zero energy challenges add emphasis to the realized performance of these daylighting systems. On average daylighting systems deliver only 50% of the expected energy savings.

This performance gap is partially related to initial commissioning issues due to lack of time, information, or expertise, and partially related to the inability of current technologies to respond to the actual daylight and occupant needs of the space (i.e., equipment limitation to track important lighting quantities in a space over time). A review of the technology requirements needed to fill this performance gap (see Appendix F) shows that the following attributes are needed for commissioning, measurement and verification, and daylighting control equipment:

- Image-based sensor: Adding spatial awareness to better determine workplane illuminance and window luminance, as well as awareness of electric lighting fixture location and status.
- Software-based controller: Allows for a flexible system to assist the initial and ongoing commissioning by prioritizing manual input such as occupant preferences and collected information such as changing space finishes and demand response signals.
- Open platform controller: Allows for integration with other building control system signals and flexibility to connect with all lighting components.

Existing products address some of these requirements. For example, WattStopper's dual-loop photosensor is a software-based controller that accounts for changing space finishes over time. The IPOS sensor is the only known technology that addresses all requirements. IPOS is a baseline technology that, with the research path presented,

¹⁹ Use cases and demonstrations are applicable to the Pacific Northwest region as well.

could be the platform for future lighting control development that combines multiple robust sensing capabilities, while emphasizing both energy savings and occupant comfort. This white paper in Appendix F outlines the current state of lighting controls, presents the gaps in energy savings, and proposes a chronological progression toward closing those gaps using IPOS technology. The chronological and prioritized steps are to use demonstration projects to:

- Measure the energy savings potential and verification of energy saving results using existing security camera imaging hardware and IPOS software. This would serve as a proof-of-concept for IPOS software to function as a measurement and verification tool. Stakeholders such as utilities need cost-effective tools to monitor potential and actual energy savings of installed energy efficiency measures to determine the efficacy of lighting control incentive and rebate programs.
- Measure the energy savings potential and verification of energy saving results using installed IPOS hardware/firmware as well as IPOS software. This would serve a proof-of-concept for IPOS software and hardware as a measurement and verification analysis tool for use by stakeholders such as utilities and ESCOs where existing imaging hardware is not available.
- For the location(s) where IPOS has been installed, and for which energy saving potential has been determined, leave the IPOS hardware in place and retrofit lamps and ballasts for integrated IPOS daylighting control. This would serve as a proof-of-concept that a measurement and verification tool for existing buildings (or a commissioning tool for new buildings) can be transitioned into an integrated daylighting control device. The improved performance of an image-based sensor over incumbent technologies would be demonstrated. This would serve a proof-of-concept for IPOS software and hardware as an integrated commissioning and daylighting control technology that realizes at least 75% of the daylighting control savings potential by addressing the initial commissioning gap.
- For the location(s) where IPOS has been transitioned into a control device, enhance the ongoing commissioning algorithm with the end goal of maintaining energy savings and improving occupant comfort for one year. This would serve a proof-of-concept for IPOS software and hardware as an integrated commissioning and daylighting control technology that realizes the full daylighting control savings potential by addressing the current technology gap of performance over time. The stakeholders for the latter two steps are owners and building managers who are responsible for ongoing daylighting energy savings implied by increasingly stringent energy codes and standards.

The value of working toward a comprehensive tool is that a common device used for multiple purposes can reduce cost and increase familiarity in the industry to reduce the need for experts in each aspect of daylighting commissioning and control. (See Appendix F for a description and analysis of daylighting controls and daylighting commissioning requirements, gaps, opportunities, and recommendations for IPOS potential in filling those gaps.)

5.2 *Daylight Harvesting and Occupancy Control*

5.2.1 Opportunity

The IPOS occupancy detection and illuminance estimation functions create a potential for future development of an integrated daylight harvester/occupancy sensor, capable of controlling multiple lighting zones using one sensor with ROIs. A multiple zone approach would allow for more localized and independent daylighting and occupancy control while potentially reducing hardware, installation, and maintenance costs. This use case was the subject of applied testing at a third-party location. (See Appendix H (Daylight Harvesting and Occupancy Control section) for a description of the applied testing demonstration setup.)

5.2.2 Preliminary Observations from Applied Testing

To date, analysis from testing activity is not complete; however, integration of the IPOS prototype with the wireless lighting product and dry runs aimed at identifying integration issues and overall solution issues prior to actual testing produced the following preliminary observations:

- 1) The USB cable connection between sensor camera and the main IPOS board is mechanically unreliable. Uneven contacts sometimes do not ensure good electrical connection with the sensor camera. This condition was found during the frequent handling of the prototype for development of the communication interface with the gateway, which required repeated connections and disconnections from the IPOS prototype.
- 2) Observation of dimming levels and illuminance values while in operation show that the IPOS prototype provides the gateway with correct dimming levels during daytime. Lighting zone 1 (closer to the windows) was consistently receiving a lower power level than zone 2.
- 3) There is a latency of occupancy detection. The first detection delay observed was about 15-20 seconds.
- 4) On several occasions, the camera would not go into an auto-gain disabled mode after repeated manual power cycles of the IPOS prototype while developing the gateway communication interface. As a consequence, the two image sets produced (one with auto-gain enabled, and the other with auto-gain disabled) were both optimally exposed. Although this did not have an adverse effect on the detector functions, it had an impact on the illuminance estimation function, resulting in low estimates (often zero values) that affected dimming functionality.
- 5) During a dry run, it was observed that lighting power levels for the two zones were consistently excessive compared to available daylight. Based on daylight availability, electric light levels should have been at low dimming values and not at full power. Analysis of prototype logs and sensor image captures revealed that the sensor's field of view of the two ROIs was obstructed by an office chair. The chair's dark fabric caused illuminance readings to fall consistently lower than the

low setpoint, inducing the dimming function to generate high lighting power levels.

- 6) On an overnight run with IPOS controlling lights in the conference room, logs indicated high illuminance readings for long periods of time after dusk and during the night. The illuminance value readings and log analysis suggested that lights were turned on at night because of false positives. Further analysis revealed that the source of the false positives was the motion detection function, triggered by low daylight levels at dusk (see Section 3.4).
- 7) The prototype kept lights fully on (or dimmed) during periods of occupancy.
- 8) On a dry run during the day, it was reported that while on a conference call with occupants doing minimal motion the lights turned off. However, the occupants were seated with their faces away from the camera, which may explain why none of the three detector functions detected occupancy.
- 9) Lights were automatically turned off during periods of vacancy, as expected. However, on another dry run it was observed that at times lights transitioning to off after a period of occupancy caused the motion sensor function to pick up the sudden lighting change as new motion, which in turn caused the lights to be turned back on.
- 10) It was observed that the motion detection function did not register occupants under low illuminance levels (lower than 5-10 Fc).

5.2.3 Recommendations and Future Developments Based on Applied Testing Results

Recommendations based on the 10 observations from the IPOS applied testing are summarized in Table 8, as well as recommended development, action plan, and suggested timing.

Observation Number	Short Term	Longer Term	Plan
1			Not an issue in an integrated product. Strictly a limitation of the prototypes.
2			No action needed.
3	X		Investigate alternative means of collecting and feeding image captures to the sensor and estimation functions (with and without auto-gain settings).
4			Resolved with a script modification.
5			Performs as expected. Can be addressed with a higher mounting location.
6			This issue was resolved with a calibration of the motion sensor function. In addition, software has been modified so that the motion detection function is turned off when illuminance levels fall below a user-defined threshold.
7			No action needed.
8		X	Expected behavior. A user-controllable motion sensitivity setting may be desired.
9	X		Investigate methods for discriminating sudden brightness changes from motion.
10			No action needed. This is an expected behavior (see Section 3.4).

Table 8: Recommended next steps for IPOS used as daylighting harvester and dimming control

As Table 8 shows, additional development is needed in the short term to address latency of the image acquisition process²⁰, and algorithm changes to the motion detection function to rule out brightness changes as motion. New training sets for the face and people detector functions may also be required if IPOS is used on existing ceiling mount locations (as a replacement for daylight harvesters), where occupants would need to be detected from directly above.

In the short and medium terms, collaborative research and development is recommended to advance the technology (in particular, to address items 3 and 9 from Table 8). The collaborative work may focus on value proposition development (short term), access to several demonstrations to assess technology and occupant comfort (medium term), and cost reduction (longer term). A user interface for sensitivity settings and virtual zones configuration is recommended.

5.3 Occupancy and Event Logger, Occupancy Analysis

5.3.1 Opportunity

Utilities need a way to verify occupancy and daylighting energy savings for the evaluation and design of incentive programs or rebates. This use case actually represents a family of use cases. In addition to occupancy, illuminance and other variables, IPOS may be used to read, log, aggregate, and report (online or off-line) on a

²⁰ Latencies below 2 seconds are considered acceptable.

number of variables of interest. Use cases in this category may include the following examples:

a) **Analysis of walk-in refrigeration use.**

With additional software and hardware changes, IPOS can inform on door state (open/closed) of walk-in refrigerators or freezers and report it along with occupancy near the doors, effectively replacing the need for separate data logging or dedicated instrumentation. The additional variables are collected and logged by IPOS, so correlation of occupancy information with physical/electrical state is facilitated and can be more easily aggregated, analyzed, and reported.

b) **Occupancy monitoring and analysis for parking areas.**

Occupancy logging may provide information to estimate and verify energy savings. The lighting levels can also be reported during occupied and unoccupied periods. This use case may be able to use images from existing security cameras or installed webcams to provide information about cars and people.

Illuminance information may inform future energy saving measures or safety issues. Once data is collected and analyzed at the IPOS level, IPOS may also be able to aggregate and generate summary data to be sent regularly (daily or weekly, for example), for post-processing and dissemination to interested parties or for further analysis and evaluation.

c) **Occupancy schedule analysis and reporting for largely unoccupied areas.**

Data centers, mechanical rooms, telecommunications and data networking closets, electrical panel rooms, or other infrequently occupied areas of commercial buildings present opportunities for energy savings through a better understanding of occupancy patterns and schedules in relation to other energy uses (for example, ventilation, temperature management, or lighting). An application leveraging concepts similar to the previous use case could be used in infrequently occupied areas to report through aggregate summaries. This information can be potentially processed locally at the IPOS sensor level or sent for remote processing.

NREL is currently involved in a preliminary test for the analysis of walk-in refrigeration use at a large retail store in Colorado. As part of the use case, IPOS monitors occupancy in the proximity of a walk-in freezer, and freezer door open/closed state in an effort to better understand the potential for energy savings improvements (outside of normal loading and unloading cycles) due to doors left open for long periods of time without anyone loading or unloading.

Currently, no sub-metering or door state logging exists for walk-in freezers at this location, making an assessment of door usage extremely difficult or very costly to determine. The IPOS occupancy function can be used in conjunction with door state detection (open/closed) and associated occupancy state. IPOS can take the place of an expensive distribution-level sub metering installation, to obtain detailed data sets of

heterogeneous information. (See Appendix H (Occupancy and Event Logger, Occupancy Analysis of Walk-in Freezers) for a description of the demonstration setup.)

5.3.2 Preliminary Results

Three comma-separated value (CSV) files, corresponding to three separate data downloads, were analyzed for occupancy periods and periods of door left open with no occupancy. Table 9 shows preliminary results.

Log Length (Days)	Total Hours Door Open	Total Hours Door Open and Unattended	Total Hours Door Open and Unattended for Periods Longer Than 10 Minutes	Total Hours/Day Door Open and Unattended for Periods Longer Than 10 Minutes
13.1	85.5	58.5	47.3	3.6
29.2	228.7	167.7	140.3	4.8
29.3	249.8	175.6	146.6	5.0

Table 9: Times of Open and Unattended Door for a Walk-In Freezer

The following are preliminary observations:

- 1) The CSV records file is currently stored in volatile memory of the IPOS prototype device. A brief power interruption at the store caused two months worth of data to be lost. However, IPOS was never intended to be used as a data logger, and was not fitted with nonvolatile storage.
- 2) Sporadic false occupancy events were reported by the face and people detection functions. Figure 20 shows two such events with the door open. Conversely, a typical correct identification is shown in Figure 21.



Figure 20: False Positives (Left: Face; Right: People) at a Walk-In Freezer (Luigi Gentile Polese/NREL)

- 3) The images in Figure 20 clearly show no occupants in sight with door open. However, because the face and people detection functions generated occupancy events in these and other cases (due to the false positive), occupancy analysis from false reported occupancy events contributed to a conservative estimate of the time of door open and left unattended.



Figure 21: People detection at a walk-in freezer (Luigi Gentile Polese/NREL)

- 4) Analysis of the false face and people detection events revealed a consistent recurrence at the same approximate coordinate locations over time.
- 5) Door state logging was accurate with 1-second accuracy. The time resolution depends on the main loop function used for reading the door state, which is executed once per second.
- 6) Occupancy detection latency (time from true occupancy to IPOS reporting occupancy) was about 15-20 seconds, due to reasons described in the “Image Acquisition Considerations” section. This latency can also be inferred through the CSV file, clearly showing a door open event followed by an occupancy event some 15-20 seconds later.

5.3.3 Recommendations and Future Developments

Table 10 summarizes recommended technology developments for the analysis of walk-in refrigeration use case, action plan and suggested timing. Such developments are necessary steps for future case study and commercialization plans.

Observation Number	Short Term	Longer Term	Plan
1		X	For logging and long term data collection and summary reporting applications, use of permanent memory storage will be required.
2		X	Investigate the use of custom training sets specific to the use case, to improve detection accuracy.
3			No action required. Will be resolved by addressing # 2.
4	X		Investigate a simple algorithm change for excluding sources of false detection through user configuration (see Appendix G).
4		X	Investigate algorithm changes for the development of a post-commissioning self-training algorithm for excluding sources of false detection during normal operation of the sensor after a training period (see “Individual Detectors Accuracy” section).
5			Performs as expected. If a different resolution is desired, logging frequency may be performed independently from other software execution.
6	X		A simple post-processing of the spreadsheet to transpose the occupancy timestamps can easily correct this delay. Actual fix involves investigating alternative means of collecting and feeding image captures to the sensor functions.
6		X	Address latency in delivering images to the sensor functions. Investigate alternative means of collecting and feeding image captures.

Table 10: Recommended Next Steps for IPOS Used as Occupancy and Door State Event Logger

Relationships with Better Building Alliance members could be leveraged for future improvements of the technology and demonstrations projects. Similar considerations apply in terms of market and licensing and commercialization opportunities. Discussions with several Better Building Alliance members underscore the need for monitoring mechanical equipment, both from a diagnostic perspective, and from an optimal energy use point of view.

Potential future collaborative work may focus on identifying top needs from commercial building owners and operators, services companies, and develop business cases for each, evaluating value propositions and action plans.

With action plans defined, a future phase involving focused development, technology improvements, cost reduction, and access to demonstrations sites to advance the technology is recommended.

Focused development is recommended to address latency of the image acquisition process, and algorithmic changes are required to minimize false positives through development of specific training sets or exclusion of false positives through intelligent algorithms able to recognize and eliminate sources of false positives.

Development of a new function is also recommended for implementing the data aggregation and summary generation and streaming according to the specific requirements gathered during collaborative work for business case development.

Potential developments in the short term for use cases b) and c) may include definition of the variables to be reported, which in turn would inform on the need for hardware and software changes. Other short-term recommendation is the investigation and development of prototypes able to work outdoors under extreme weather conditions. This includes not only cameras, but also the processing and memory components as well. Hardware designed for extreme weather can drive costs significantly higher and may hamper business case for commercialization purposes. Type of aggregate data, frequency of reporting and modality of delivery of the summary data will inform on software changes, improvements and memory capacity requirements.

Longer term, successful completion of the short-term recommendations for the three use cases may inform potential evolution of IPOS into a data analysis project activity where NREL could provide technical support to a third-party pilot test site by defining data collection plan, deploying devices, infrastructure, project management and providing occupancy analysis through collected streamed data.

5.4 *Interactive Exhibits*

5.4.1 Opportunity

A potential application of the IPOS sensor is to use the technology as an aid for interactive audio and visual marketing and advertising. The combined functions of IPOS for activity, motion, faces, people, and occupant location detection has the potential for turning on/off lights, to start or stop playing videos or commercials when occupants approach a screen or an exhibit, or to control animations for promoting products or services.

The sensor could be deployed in commercial spaces where exhibits or interactive marketing material are located and greater energy savings are desired. Potential market opportunity includes museums, visitor's centers, retail sales or showrooms where there is display, advertising and promotion of product or services.

NREL has plans in FY 14 to evaluate the use of an IPOS prototype as an aid for interactive audio and visual exhibits at the Education Center²¹. The occupancy signals generated by the prototype will be utilized to control the brightness levels of a large touch screen exhibit. (See Appendix H (Interactive Exhibit section) for a description of the demonstration setup.)

5.4.2 Recommendations and Future Developments

In the short and medium term, the lessons learned from the NREL Education Center demonstration will inform on energy savings potential specific to museum environments. Besides required technology improvements, new interfaces may also need to be developed for additional sensing and for controlling multiple sources (lights, video, music, or multimedia) for advertising, presentation, or promotion purposes.

²¹ Formerly known as NREL Visitors Center.

In the medium and long term, utilities may be able to benefit from results of energy saving studies for the development of utility rebates specific to museums, to offset portion of upfront costs sustained by museums to add the technology to existing lighting systems. Potentially, deeper rebate or incentive programs may be additionally designed for museums willing to also switch to higher efficiency lighting (for example, LEDs) when combined with the IPOS, to partially offset retrofit project costs.

5.5 *Light Logging and Lighting Sub-Metering*

5.5.1 Opportunity

Because of the potential for IPOS to provide illuminance level estimates from image analysis, the sensor may be used in applications unrelated to occupancy. One such application recommended for further development is to log estimated electric lighting state (on, off and dimming level) to estimate lighting energy consumption, and inform energy saving opportunities²², effectively replacing expensive dedicated submetering equipment.

The collected data can potentially inform on new product performance and also help evaluate alternative control algorithms for optimal operation. Lighting and daylighting data in the form of lighting schedules and profiles can feed into building models for realistic lighting studies. (See Appendix H (Light Logging/Light Submetering section) for a description of the demonstration setup.)

5.5.2 Recommendations and Future Developments

Besides gaining additional experience with sensor performance and required sensor modifications, a recommendation for the short term is to start additional small pilot projects for new case studies.

One such case study of potential interest to utilities and providers in the short term may be to collect electric lighting and daylighting data to support new or existing incentive programs. In such data collections, power consumption and dimming state of fluorescent ballasts can be inferred from illuminance level readings of the light fixtures. Similarly, workplane illuminance levels can also be estimated using the IPOS sensors configured with multiple independent ROIs. This data can support the development of standardized occupancy and daylighting verification protocols, for the cost-effective verification of daylighting energy savings.

Longer term, there is opportunity for data logging of interior and exterior²³ lighting in relation to available daylighting to inform on utility rebates or incentives for new energy efficient lighting technologies.

²² The use case does not directly submeter electric energy; rather, energy consumption can be inferred and estimated from electric light levels.

²³ Applications for exterior environments will require extensive modifications to IPOS due to weather exposure.

5.6 *Demand Controlled Ventilation Control*

5.6.1 **Opportunity**

The sensor capability of providing number of occupants, approximate spatial location of occupants and activity levels has potential for use in demand controlled ventilation (DCV) control applications to modulate ventilation in several virtual zones through a single IPOS. Number of occupant detection is the main driver for DCV capability, as it replaces CO₂ sensing²⁴, which is a surrogate for this quantity. An example of use case implementation is documented in [6].

5.6.2 **Recommendations and Future Developments**

In the short term, an evaluation of IPOS sensor and installation costs in new buildings and retrofits is recommended for value proposition and business case development. From a technical perspective, the occupant location demonstration function would need to be modified to implement an algorithm based on [6] or a variation of it, and early DCV demonstration projects and sites identified. Commercialization efforts may be started following value proposition and business case development.

Longer term, utilities may be interested in evaluation studies and analysis of ventilation energy reduction opportunities.

5.7 *Temperature Management*

5.7.1 **Opportunity**

This use case is similar to the DCV control opportunity, except that IPOS provides approximate occupant spatial location and activity level. This use case also has the potential for use as dynamic temperature setpoint management in new construction or retrofits. Similarly, an example of use case implementation from a technical perspective is documented in [6].

The activity detection function, along with the occupant location estimation function would be used to inform whether temperature settings and setpoints should be changed from a pre-set schedule to minimize unnecessary heating and cooling.

5.7.2 **Recommendations and Future Developments**

Similar short term and long term recommendations for the DCV control use case apply for the temperature management use case.

In the short term, it is recommended that early demonstration projects be identified and evaluated in terms of technology and costs, to inform necessary technology developments and potential direction to commercialization efforts.

²⁴ Through occupant count and estimated carbon dioxide emissions generated by the occupants in relation to activity levels. However, IPOS was not evaluated with regard to ASHRAE 62.1.

Longer term, similar to the DCV use case, utilities may be interested in evaluation studies and analysis of HVAC energy reduction opportunities. Sensor cost reductions analysis (and market opportunity) is recommended. Cost reductions may be achieved when combining IPOS functions. A further reduction in the number of sensors may be achieved with a combination of multiple virtual zones implemented in a single sensor, and/or an increased field of view of the camera.

5.8 *Space Planning and Management*

5.8.1 Opportunity

IPOS has potential for use as a tool or as a component of a larger application that provides feedback to space planning and space management systems. Such systems inform space management and planning organizations on building defragmentation opportunities and efficient utilization of the spaces and assets. IPOS could be employed in a real-time conference room scheduling based on present occupancy.

A potential use case may be for IPOS to feed data into a tool providing aggregate occupant count and location to feed visualizations, or to provide summary data over periods of time. Users of the tool would be able to make objective, informed decisions about occupant reallocations to defragment space utilization and subsequently modify temperature, lighting, and ventilation setpoints to optimize and reduce energy use from lighting and mechanical loads.

For example, in office or in education environments actual building utilization may be sparse. This presents an opportunity for occupant consolidation and therefore reducing cooling, heating, lighting, and energy consumption. IPOS could provide key data for visualizing (on a building map, for example) actual occupancy, to help identify occupant consolidation opportunities. This provides a unique use case for space planning and real estate portfolio management organizations.

In another use case not focused on energy savings, data based on people count, densities, location in relation to time of day, or other variables can potentially help inform retail, marketing and sales studies and optimize potential shopper traffic flows and/or develop new point of sale marketing strategies.

5.8.2 Recommendations and Future Development

In the short term, an evaluation of the business case, value proposition, and quantification of energy savings opportunities is recommended.

Longer term, utilities may be interested in evaluation studies for incentives development based on auditing, space planning tool use, or processes to optimize occupant distribution and building loads use in new construction and retrofits.

6 Conclusion

The IPOS has potential to evolve into a device that enhances building control systems by applying commercially available components. The richness of the information collected and synthesized by the device will result in improvements over current occupancy sensing configurations and may establish a foundation for the development of new control algorithms that achieve greater levels of energy efficiency and occupant comfort.

By continuing to rely on existing occupancy sensor technology, we are bound to limit the effectiveness, and thus efficiency, of control systems. This impacts the building users and the energy usage of the building. IPOS has potential to offer the technology to more accurately understand the occupant activity within buildings and thus it may permit a more finely grained control scheme to be implemented. Without this knowledge of activity, we may continue to waste lighting and HVAC resources and, at the same time, utilize a control system that disrupts users as a result of limitations in their operation methods.

The IPOS technology has potential to help further the BPA's leading role in conservation programs in the commercial sector by expanding the number of tools made available to end users to realize energy efficiency goals.

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Appendix A – Luminance Assessment Method

The camera sensor used for the demonstration, an e-CAM33_USB from e-con Systems, had a provision for software-driven exposure controls. The image acquisition function drives the camera periodically into two auto-gain states: enabled, and disabled. Two sets of images are stored in temporary buffers for processing. Figure A 1 shows an example of image captures from the two sets: with auto-gain enabled (left), and without auto-gain set (right).



**Figure A 1: Normally Exposed Image Capture (Left);
Image Capture with Camera Auto-Gain Disabled (Right)**

Several readings (Table A 1) were collected with IPOS producing digital values from the luminance estimation function and with a reference Data Logging Light Meter [10] placed in the same field of view as seen from the camera sensor. The test location was an open office space with luminance values ranging between 24 and 44 Fc.

IPOS Digital Readings (Average Pixel Value)	Light Meter Readings (Fc)
147.52	24.50
146.71	24.40
146.60	24.30
169.99	34.80
175.12	34.87
174.29	34.75
175.82	34.57
175.74	34.47
248.80	44.40
248.87	44.30
249.04	44.40

Table A 1: IPOS Digital Readings and Light Meter Reading Values

A polynomial regression equation was determined from the two sets of values, giving the following equation:

$$l = -2.391921639 \cdot 10^{-3} d^2 + 1.141801507 d - 91.65375431$$

where **l** is the estimated luminance in Fc, and **d** is the digital reading from the luminance assessment function. The resulting calibration curve (Figure A 2) has a residual sum of squares of 3.04 and a maximum error of 1.48 Fc.

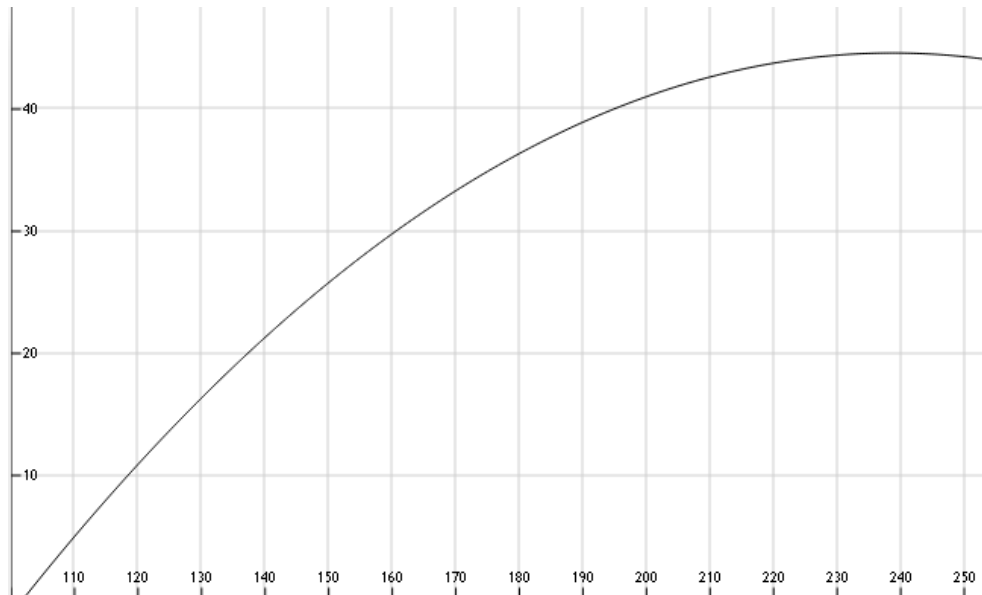


Figure A 2: Luminance Assessment Calibration Curve
(X Axis: Digital Reading; Y Axis: Estimated Fc)

The equation coefficients are passed-in to the luminance assessment function through a user-modifiable file. Luminance estimates produced by the luminance assessment function are logged to a file, sent over BACnet and serial connection, and used internally to produce dimming level outputs.

Appendix B – Dimming Levels Function

Dimming levels are generated in the IPOS prototype from the estimated illuminance values for the entire image and each ROI. A user-configurable file accepts the following inputs for the dimming function:

- A low setpoint, in Fc
- A high setpoint, in Fc
- Dimming rate (discrete, continuous)
- Number of dimming steps (if discrete dimming)
- Maximum dimming increment/decrement percentage

These inputs could be exposed in a future daylighting commissioning user interface to configure lighting control zones for IPOS.

The two setpoints define the range of illuminance values in which dimming will be active. Any estimated illuminance equal or lower than the low setpoint value will produce zero dimming (or 100% lighting power), therefore generating a numeric power value that can be used to drive lights fully on. Illuminance values equal or greater than the high setpoint value will produce full dimming (or 0% lighting power), therefore generating a power level value that can be used to turn lights fully off. Figure B 1-Figure B 2 show the equivalent dimming curves for continuous dimming and 10 dimming steps, respectively.

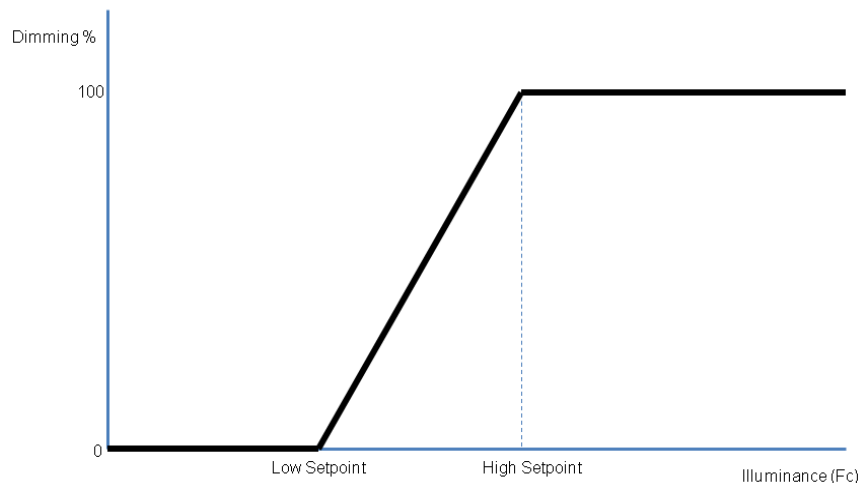


Figure B 1: Dual Setpoint Configuration for Continuous Dimming Function

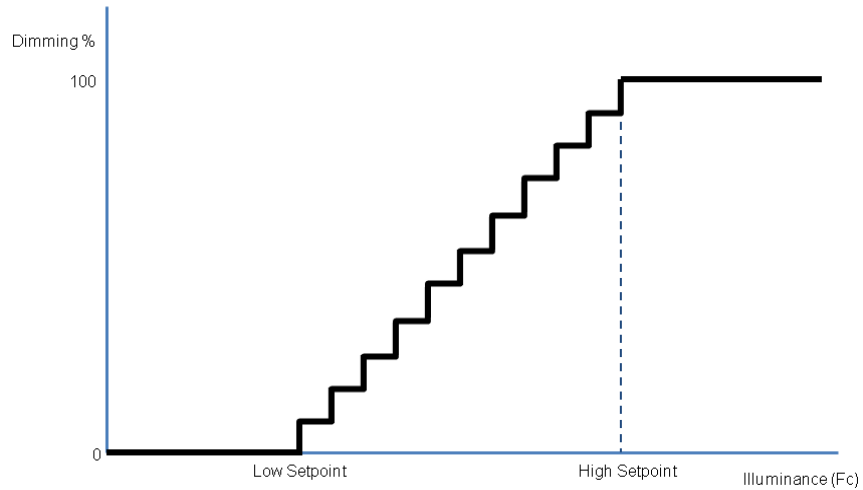


Figure B 2: Dual Setpoint Configuration for 10 Discrete Dimming Steps

The maximum dimming increment/decrement percentage is a parameter used in the demonstration algorithm to provide a smooth dimming transition between consecutive evaluation cycles. The maximum increment/decrement percent value, which for the IPOS dimming demonstration was set to a default of 5%, limits the power level change from the previous evaluation cycle to a maximum of 5%. Limiting the power level ensures a smooth transition when light levels change significantly between evaluation cycles, therefore making the light level adjustments unnoticeable to the occupants and providing a slower convergence to the optimal dimming level over time.

Appendix C – IPOS BACnet Message Definitions

The outputs received from the sensor integration are properly mapped and transmitted via the BACnet protocol according to IPOS-specific message extension definitions (Table C 1).

Property	Value	Output
PROP_OBJECT_NAME (77)	OCCUPIED, OCCUPIED_ZONE_x	OCCUPIED, OCCUPIED_ZONE_x
PROP_PRESENT_VALUE (85)	Occupied	ACTIVE, ACTIVE_ZONE_x
PROP_OCCUPANCY_STATE (296)	Active	
PROP_OCCUPANCY_COUNT (290)	NumberOccupy	Analog Outout
PROP_RESOLUTION (106)	Confidence	LUMINANCE, LUMINANCE_ZONE_x
PROP_ZONE_UPPER_LEFT_X (5131)	OccZoneUpperLeftX	DIMMING, DIMMING_ZONE_x
PROP_ZONE_UPPER_LEFT_Y (5132)	OccZoneUpperLeftY	CONFIDENCE, CONFIDENCE_ZONE_x
PROP_ZONE_LOWER_RIGHT_X (5133)	OccZoneLowerRightX	NUMBER_OCCUPANTS,
PROP_ZONE_LOWER_RIGHT_Y (5134)	OccZoneLowerRightY	NUMBER_OCCUPANTS_ZONE_x
		UPPER_LEFT_X_ZONE_x
		UPPER_LEFT_Y_ZONE_x
		LOWER_RIGHT_X_ZONE_x
		LOWER_RIGHT_Y_ZONE_x
PROP_OBJECT_NAME (77)	LUMINANCE	
PROP_PRESENT_VALUE (85)	Luminance	
PROP_ZONE_UPPER_LEFT_X (5131)	LumZoneUpperLeftX	
PROP_ZONE_UPPER_LEFT_Y (5132)	LumZoneUpperLeftY	
PROP_ZONE_LOWER_RIGHT_X (5133)	LumZoneLowerRightX	
PROP_ZONE_LOWER_RIGHT_Y (5134)	LumZoneLowerRightY	

Table C 1: IPOS BACnet Message Extension

The demonstration prototype currently sends the following outputs for the whole image and up to eight user-definable ROIs:

- Composite occupancy
- Composite confidence level
- Activity level
- Illuminance reading
- Dimming level
- Number of occupants
- ROI coordinates

Appendix D – IPOS Prototype Test Procedures

Unit Tests

Unit testing was the lowest level of testing performed on the prototype. The software functions were evaluated for language-specific programming errors such as bad syntax, unintended logic errors, or to assess code that cannot be easily evaluated under ordinary conditions. We designed unit test cases (see below) to verify that algorithms functioned as intended, and that erroneous or abnormal conditions were handled appropriately. The prototype was exposed to a variety of conditions to achieve coverage in terms of space types, lighting levels, occupancy, and occupant activities. The tables below describe the unit tests developed.

Test Type	Unit
ID	Image Acquisition-1
Abstract/Title	Image frames captured without interruptions
Test Description	Frames collected reliably at regular pre-determined interval, stored in memory, accessible for analysis
Item(s) to be tested	
1	Camera connected to the device, or previously saved image frames
Procedure	
1	Frames are captured and stored in memory as numbered files from 1 to ACQUIRE_MAX_FILES, then overwritten starting at frame 1
2	Frames format stored according to configuration
3	Frames are acquired at regular ACQUIRE_SLEEP intervals with no interruptions (skip if frames were previously stored)
4	With the camera acquiring images and a camera monitoring window, open several frame capture files
5	Verify files can be opened, inspect frames comparing with scene from live monitoring window
6	Verify image files are renewed/overwritten with latest captures

Test Type	Unit
ID	Motion Detection-1
Abstract/Title	No motion in captured frames
Test Description	Verify the motion detector reports no motion
Item(s) to be tested	
1	IPOS motion detector
Procedure	
1	Image acquisition function capturing frames for a scene with no occupants and no moving objects (or have previously captured frames in memory for processing)
2	Open live camera (skip this if captures already collected) and motion detector monitoring windows
3	Verify scene has no moving objects or people
4	Verify motion detector monitoring window is black (no motion differences between frames)
5	Verify the motion detector reports no areas moving and very low average motion (a low average motion is normal due to pixel noise reported from the camera)
6	Verify motion detector reports vacancy with confidence greater than 90%

Test Type	Unit
ID	Motion Detection-2
Abstract/Title	Small motion in captured frames
Test Description	Verify the motion detector reports motion
Item(s) to be tested	
1	IPOS motion detector
Procedure	
1	Image acquisition function capturing frames for a scene with one occupant seated at a desk, typing at the computer (or have previously captured frames in memory for processing). Camera distance is about 20ft from target
2	Open live camera (skip this if captures already collected) and motion detector monitoring windows
3	Verify captures have occupant doing small motions while typing
4	Verify motion detector monitoring window shows movements of the hands
5	Verify the motion detector reports 1 or >1 areas moving and motion
6	Verify motion detector reports occupancy with confidence greater than 70%

Test Type	Unit
ID	Face Detection-1
Abstract/Title	No frontal faces in captured frames
Test Description	Verify the face detector reports no faces detected
Item(s) to be tested	
1	IPOS face detector
Procedure	
1	Image acquisition function capturing frames for a scene with one occupant standing, face away from camera (or have previously captured frames in memory for processing). Camera distance is about 10ft from target
2	Open live camera (skip this if captures already collected) and Haar detector monitoring windows
3	Verify scene has occupant standing with the face away from the camera
4	Verify the face detector reports no faces detected
5	Verify the face detector reports no face occupancy with confidence greater than 90%

Test Type	Unit
ID	Face Detection-2, Face Detection-3
Abstract/Title	Frontal face in captured frames
Test Description	Verify the face detector reports face detected
Item(s) to be tested	
1	IPOS face detector
Procedure	
1	Image acquisition function capturing frames for a scene with one occupant standing, face towards camera (or have previously captured frames in memory for processing). Camera distance is about 10ft from target
2	Open live camera (skip this if captures already collected) and Haar detector monitoring windows
3	Verify scene has occupant standing with the face towards the camera
4	Verify the face detector reports >0 faces detected
5	Verify the face detector reports face occupancy with confidence greater than 70%
6	Repeat with two people standing, facing towards camera
7	Verify the face detector reports face occupancy with confidence greater than 90%

Test Type	Unit
ID	People Detection-1
Abstract/Title	No occupants (people) in captured frames
Test Description	Verify the people detector reports no people detected
Item(s) to be tested	
1	IPOS people detector
Procedure	
1	Image acquisition function capturing frames for a scene with no occupants (or have previously captured frames in memory for processing)
2	Open live camera (skip this if captures already collected) and people detector monitoring windows
3	Verify scene has no occupant
4	Verify the people detector reports no people detected
5	Verify the people detector reports no people occupancy with confidence greater than 90%

Test Type	Unit
ID	People Detection-2, People Detection -3, People Detection -4
Abstract/Title	One or more occupants standing in captured frames
Test Description	Verify the people detector reports people detected
Item(s) to be tested	
1	IPOS people detector
Procedure	
1	Image acquisition function capturing frames for a scene with one occupant standing, no obstructions between camera and occupant (or have previously captured frames in memory for processing). Camera distance is about 15ft from target
2	Open live camera (skip this if captures already collected) and people detector monitoring windows
3	Verify scene has occupant standing
4	Verify the people detector reports >0 people detected
5	Verify the people detector reports occupancy with confidence greater than 70%
6	Repeat with two people standing, no obstructions
7	Verify the people detector reports occupancy with confidence greater than 90%
8	Repeat with two people standing, partial obstruction between camera and occupants (>0 legs partially visible)
9	Verify the people detector reports occupancy with confidence greater than 50%

Test Type	Unit
ID	Activity Level Assessment-1
Abstract/Title	No activity in captured frames
Test Description	Verify the activity level function reports sedentary activity
Item(s) to be tested	
1	IPOS activity level function
Procedure	
1	Image acquisition function capturing frames for a scene with no occupants and no moving objects (or have previously captured frames in memory for processing)
2	Open live camera (skip this if captures already collected) and motion detector monitoring windows
3	Verify scene has no moving objects or people
4	Verify motion detector monitoring window is black (no motion differences between frames)
5	Verify the activity level function reports very low average motion (a low average motion is normal due to pixel noise reported from the camera)
6	Verify the activity level function reports sedentary activity

Test Type	Unit
ID	Activity Level Assessment -2, Activity Level Assessment -3, Activity Level Assessment -4
Abstract/Title	Activity levels in captured frames
Test Description	Verify the activity level function reports activity
Item(s) to be tested	
1	IPOS activity level detection
Procedure	
1	Image acquisition function capturing frames for a scene with one occupant seated at a desk, typing at the computer (or has previously captured frames in memory for processing). Camera distance is about 20ft from target
2	Open live camera (skip this if captures already collected) and motion detector monitoring windows
3	Verify scene has occupant doing small motions while typing
4	Verify motion detector monitoring window shows movements of the hands
5	Verify the activity level function reports low average motion (just above motion detection threshold), in the range category classified as sedentary activity
6	Repeat with scene showing occupant standing, with arms moving and small body movement
7	Verify the activity level function reports higher average motion, in the range category classified as vigorous activity
8	Repeat with scene showing occupant walking
9	Verify the activity level function reports high average motion, in the range category classified as vigorous activity

Test Type	Unit
ID	Luminance Assessment-1, Luminance Assessment -2, Luminance Assessment -3, Luminance Assessment -4
Abstract/Title	Luminance assessment
Test Description	Verify algorithm
Item(s) to be tested	
1	IPOS luminance assessment
Procedure	
1	Use four frame captures of office spaces with known average luminance levels
2	Record IPOS luminance assessment; report accuracy (within or beyond $\pm 20\%$ tolerance)

Test Type	Unit
ID	Sensor Integration-1
Abstract/Title	Sensor integration function receiving data from all active sensors
Test Description	Verify sensor integration receives sensors data
Item(s) to be tested	
1	IPOS sensor integration function
Procedure	
1	Image acquisition function capturing frames for a scene with occupants standing up, facing towards camera (or have previously captured frames in memory for processing)
2	Open live camera (skip this if captures already collected) and detector monitoring windows (motion, face, people)
3	Verify scene has occupants as described in step 1
4	Verify motion, face and people detectors report occupancy with a high confidence level (>70%)
5	Verify the motion detector reports areas moving and medium average motion
6	Verify sensor integration receives occupancy data from all of the active detectors: occupancy value (occupied/vacant), confidence level (0.00 to 1.00), activity level (sedentary/vigorous)

Test Type	Unit
ID	Sensor Integration -2, Sensor Integration -3
Abstract/Title	Occupancy and confidence level estimation algorithm
Test Description	Verify occupancy algorithms
Item(s) to be tested	
1	IPOS sensor integration
Procedure	
1	Image acquisition function capturing frames for a scene with occupants standing up, facing towards camera (or have previously captured frames in memory for processing)
2	Open live camera (skip this if captures already collected) and detector monitoring windows (motion, face, people)
3	Verify scene has occupants as described in step 1
4	Verify sensor integration receives occupancy and confidence levels from motion, face and people detectors, respectively
5	Verify sensor integration receives activity level data
6	Verify calculation of the <i>OccupiedFilter</i> variable. Verify that the sensor integration function reports occupancy if <i>OccupiedFilter</i> is above the OCCUPIED_THRESHOLD value, or if any of the active detectors reports occupancy. Verify the <i>OccupiedFilter</i> value is updated (decays) at each loop iteration
7	Verify the sensor integration function reports confidence level as a weighted average calculated with confidence levels reported by the motion, face and people detectors
8	Repeat test with a scene showing sedentary activity, one face detected, no people detected
9	Verify the sensor integration function reporting of occupancy and confidence level is according to algorithm

Test Type	Unit
ID	BACnet Integration-1, BACnet Integration -2
Abstract/Title	BACnet integration function sending data from sensor integration function
Test Description	Verify BACnet Integration sends occupancy data
Item(s) to be tested	
1	IPOS BACnet Integration
Procedure	
1	Image acquisition function capturing frames for a scene (or have previously captured frames in memory for processing). Activity level consistent with occupancy
2	Open live camera (skip this if captures already collected)
3	Verify sensor integration function is reporting occupancy
4	Verify occupancy value (1) and confidence level loaded into BACnet message structure (or message file)
5	Repeat with scene and activity level consistent with vacancy
6	Verify occupancy value (0) and confidence level loaded into BACnet message structure (or message file)

Image Sets for Unit Tests

We used a USB-connected camera (Logitech C910 HD, image size 640x480 pixels) and camera capture software to generate short sequences of image captures, stored in computer memory and used as input for the tests. Each image set contains approximately 25 frames.

For the illuminance unit tests, sequences 7 thru 10 in Table D 1 were accompanied by corresponding readings using a Extech HD450 Data Logging Light Meter. Illuminance readings were used as comparison. Also, image capture frame sequences (1 through 6) were created.

Sequence Number	Sequence Name	Description
1	NoOccupantsHallway	Hallway along windows, Open Office area, no occupants
2	OneOccupantAtPC-1	One occupant seated at the desk, light typing movements, natural light
3	OneOccStandingFaceAway	One occupant standing, face away from camera, upper body only visible
4	OneOccStandingFaceTowardsCam	One occupant standing, face towards camera, upper body only visible
5	OneOccStandingWholePerson	One occupant standing, face towards camera, whole person visible
6	ThreeOccStandingOnePartiallyObs	Three occupants in the scene (Open Office space). One occupant is partially obstructed by a board and book cabinet, one is standing face towards camera, the third one is distant, facing away from camera
7	Illuminance/ConfNoWindows24-36Fc	Small conference room. Reference light meter reports 24 Fc to 36 Fc
8	Illuminance/Desk17-20Fc	Desk work plane in Open Office space. Reference light meter reports 17 Fc to 20 Fc
9	Illuminance/EnclOffice16-22Fc	Enclosed Office space. Reference light meter reports 16 Fc to 22 Fc
10	Illuminance/OpenOffice09-18Fc	Open Office space. Reference light meter reports 9 Fc to 18 Fc

Table D 1: Test Image Capture Sequences

Image Sets for Functional Tests

Figure D 1 through Figure D 5 show the actual views taken from the camera used to create the image sets.

Conference Room

A small conference room (“huddle” room) with large display screen (on the right) for web meetings and presentations, and a white board on the left. The room can accommodate up to six participants.



Figure D 1: Conference Room (Luigi Gentile Polese/NREL)

Enclosed Office

The enclosed office is a one-person room with window, white board (right), a desk, and a PC workstation (left). The entry door is located at the opposite side from the window (behind right).



Figure D 2: Enclosed Office (Luigi Gentile Polese/NREL)

Open Office

The layout of the open office space is depicted in the following picture. The IPOS camera was placed 6 ft from the floor to maximize the field of view. Several desks and workstations are visible, along with aisles (partially), and enclosed offices in the back.



Figure D 3: Open Office (Luigi Gentile Polese/NREL)

Kitchen

A typical office kitchen with refrigerators (left) and appliances. The door (not visible) is located behind the bottom left corner of the picture.



Figure D 4: Kitchen (Luigi Gentile Polese/NREL)

Print/Copy Room

The sensor camera was placed about 6 ft from the floor (door is on the right).



Figure D 5: Print/Copy Room (Luigi Gentile Polese/NREL)

Functional Test Scenarios

Table D 2 through Table D 6 lists the test scenarios.

Space Type	Who	What	Activity	Test ID
Enclosed Office	Occupant	Sitting at the desk	Answering or talking on the phone	EO-1
	Occupant	Sitting at the desk	Typing on the computer	EO-2
	Occupant	Sitting at the desk	Conversing with another occupant	EO-3
	Occupant	Sitting at the desk	At a wall board: writing, talking, and erasing	EO-4
	Occupant	Standing up	Desk activity	EO-5
	Occupant	Sitting at the desk	Staying still, either standing or sitting	EO-6
	Occupant	Entering/Exiting from Office	Walking in/out	EO-7
	Occupant	Office is vacant	Computer screen on	EO-8
	None	Office is vacant	None	EO-9

Table D 2: Activities for Enclosed Office

Space Type	Who	What	Activity	Test ID
Open Office Space	One or more occupants	Seated at desks	Answering or talking on the phone	OO-1
	One or more occupants	Seated at desks	Typing on the computer	OO-2
	One or more occupants	Various	Conversing with another occupant	OO-3
	One or more occupants	Seated at desks	Desk activity	OO-4
	One or more occupants	Various	Staying still, either standing or sitting	OO-5
	None	Space is vacant	Space vacant, one or more computer screens on	OO-6
	One or more occupants	Various	Mixed activity (at desk, some walking or standing)	OO-7
	None	Space is vacant	None	OO-8

Table D 3: Activities for Open Office Space

Space Type	Who	What	Activity	Test ID
Conference Room	One or more occupants	Seated	At the phone	CR-1
	One or more occupants	Various	At a wall board: writing, talking, and erasing	CR-2
	None	Space is vacant	None	CR-3

Table D 4: Activities for Conference Room

Space Type	Who	What	Activity	Test ID
Kitchen	Two or more occupants	Various	Conversing with another occupant	KS-1
	One or more occupants	Entering/exiting	Walking in/out	KS-2
	None	Space is vacant	None	KS-3
	One or more occupants	Various	Activity around appliances	KS-4
	None, or one or more occupants	Dark space	None, or activity in dark/low lighting levels	KS-5

Table D 5: Activities for Kitchen

Space Type	Who	What	Activity	Test ID
Print/Copy Room	One or more occupants	Entering/exiting	Walking in/out	PR-1
	None	Space is vacant	None	PR-2
	One or more occupants	Various	Activity around printer/copier	PR-3
	None, or one or more occupants	Dark space	None, or activity in dark/low lighting levels	PR-4

Table D 6: Activities for Print/Copy Room

Live Prototype Test

Figure D 6 shows a schematic floor plan of the spaces in which the sensors were installed. Four prototypes (sensors 3 through 6) were placed in a large open space. The other two prototypes were mounted in a conference room (sensor 1) and a kitchen/break room (sensor 2). The location characteristics, orientations and field of views are summarized in Table D 7. The open office has a size of 60 feet by 180 feet from wall to wall. All IPOS cameras used in this project have a field of view of approximately 45°.



Figure D 6: IPOS Sensors Placement Locations and Fields of View (Luigi Gentile Polese/NREL)

The conference room location is a small room receiving no direct natural light, except through a glass door. Occupants usually turn off the lights after meetings, leaving the room dark during unoccupied times. This room was chosen to investigate IPOS performance during unoccupied times with relatively low lighting conditions.

The kitchen also receives no direct natural light, with indirect light received through a door. A manual light switch is usually turned on and off by the occupants, although several occupants prefer not turning lights on. There is an ultrasonic motion sensor in the kitchen; however, we found that it was disabled. This space was selected for evaluating the prototype in an area frequently occupied with low lighting levels. The remaining sensors were placed in the open area at various locations and heights, and with different orientations²⁵.

Sensor	Space Type	Daylight Present?	Sensor Placement
1	Conference room	No	Conference room B225
2	Kitchen	No	Break room B218
3	Open space	Yes	Near B216 facing east
4	Open space	Yes	Column near B208-5 facing north
5	Open space	Yes	Near B201 facing south
6	Open space	Yes	Near B201 facing west

Table D 7: IPOS Sensor Locations

Mounting positions were selected according to furniture location (to produce unobstructed views), field of view, and providing the camera sensor the best possible view and largest coverage area. Another criterion for mounting and positioning was to avoid aiming at bright light sources, such as windows or overhead light fixtures that would be sources of false positives for the motion detection function²⁶.

Each sensor logged occupancy state, confidence levels and several other variables²⁷, which were accessible through a dedicated wireless connection. Occupancy logs were updated at one second intervals. In addition, each prototype generated “raw” occupancy logs containing instantaneous occupancy data. All of the data was stored on the prototypes and periodically downloaded to a laptop for post-processing and analysis.

²⁵ The objective was not to completely cover the area; rather, it was to inform on mounting locations and monitor different areas with occupant activities and space layouts.

²⁶ Sudden changes in brightness are picked up as areas with large pixel value differences that are processed as perceived motion.

²⁷ Additional variables are: motion, face and people detector outputs, activity levels, occupant count and location information, illuminance, sensor integration variables, and BACnet outputs.

Appendix E – Vacancy Percentages Comparisons

The following tables show vacancy percentages for each period of interest and each sensor. The periods of interest are described in Table E 1:

When	Period	Times From	Times To	Comments
Weekdays	Regular Work Hours	06:00	18:00	Core hours of occupant activities
Weekdays	Cleaning shift	18:00	21:00	Occupants typically have left, cleaning crews present
Weekends¹	Day	07:00	19:00	Typically unoccupied, some daylight
¹ – includes holidays				

Table E 1: Periods of Interest for Sensor Comparisons

Table E 2 compares IPOS and PIR (with 15-minute time delay settings) vacancy times to the limit theoretically obtainable and how that varies with the number of vacancy periods in each period of interest. As the table shows, the PIR sensor achieves close to half of the maximum vacancy percentage obtainable, while IPOS exhibited a 36% improvement towards reaching that limit.

Period	IPOS/Limit	PIR /Limit
Weekdays 06:00 – 18:00	68%	26%
Weekdays 18:00 – 21:00	92%	62%
Weekends 07:00 – 19:00	88%	50%
Average, all periods	84%	48%

Table E 2: Vacancy Percentages Ratios for IPOS and PIR with a Time Delay of 15 Minutes When Compared to Theoretical Limit

Sensor	Location	IPOS	PIR (TD ₅)	PIR (TD ₁₀)	PIR (TD ₁₅)	PIR (TD ₂₀)	Limit
5	Open space, near B201 facing south	32.8	26.4	21.2	18.9	17.4	38.9
6	Open space, near B201 facing west	47.6	28.2	15.5	10.8	8.58	72.7
1	Conference room B225	60.9	50.5	40.7	33.9	29.4	71.8
4	Open space, near B208-5 facing north	25.9	17.7	11.9	9.04	7.11	46.2
3	Open space, near B216 facing east	29.4	14.7	7.77	5.09	3.89	61.5
2	Kitchen/break room B218	50.5	35.4	22.2	15.7	12.1	70.7
3,4,5,6	<i>Average Energy Savings for the Open space</i>	33.9	21.8	14.1	10.9	9.20	54.8
All	<i>Average Energy Savings across all spaces</i>	41.2	28.8	19.9	15.5	13.1	60.3

TD_{xx} = time delay of xx minutes

Table E 3: Average Energy Savings Percentages for Weekdays 06:00 - 18:00

Sensor	Location	IPOS	PIR (TD ₅)	PIR (TD ₁₀)	PIR (TD ₁₅)	PIR (TD ₂₀)	Limit
5	Open space, near B201 facing south	62.1	56.3	49.6	44.1	40.3	67.5
6	Open space, near B201 facing west	83.8	72.7	63.9	57.6	53.3	92.1
1	Conference room B225	90.8	81.4	72.0	64.4	58.1	95.2
4	Open space, near B208-5 facing north	79.9	69.3	57.9	50.5	44.9	91.5
3	Open space, near B216 facing east	78.3	66.4	55.5	47.9	42.1	89.0
2	Kitchen/break room B218	86.7	77.3	67.1	60.2	56.1	91.6
3,4,5,6	<i>Average Energy Savings for the Open space</i>	76.0	66.2	56.7	50.0	45.1	85.0
All	<i>Average Energy Savings across all spaces</i>	80.3	70.6	61.0	54.1	49.1	87.8

TD_{xx} = time delay of xx minutes

Table E 4: Average energy savings percentages for Weekdays 18:00 - 21:00

Sensor	Location	IPOS	PIR (TD ₅)	PIR (TD ₁₀)	PIR (TD ₁₅)	PIR (TD ₂₀)	Limit
5	Open space, near B201 facing south	63.9	47.9	34.1	25.5	18.7	75.9
6	Open space, near B201 facing west	77.7	62.0	46.7	37.7	30.9	88.7
1	Conference room B225	88.9	82.5	78.5	75.3	72.2	93.2
4	Open space, near B208-5 facing north	68.1	47.2	33.0	25.0	19.8	82.3
3	Open space, near B216 facing east	68.15	51.8	37.4	28.7	21.5	82.2
2	Kitchen/break room B218	86.7	79.7	72.7	67.3	62.8	93.1
3,4,5,6	Average Energy Savings for the Open space	69.5	52.2	37.8	29.2	22.7	82.3
All	Average Energy Savings across all spaces	75.6	61.8	50.4	43.3	37.6	85.9

TD_{xx} = time delay of xx minutes

Table E 5: Average Energy Savings Percentages for Weekends 07:00 - 19:00

Period	IPOS	PIR	Difference in Vacancy Time
Weekdays 06:00 – 18:00	41.2%	15.5%	25.7%
Weekdays 18:00 – 21:00	80.3%	54.1%	26.2 %
Weekends 07:00 – 19:00	75.6%	43.3%	32.3%
Average, all periods	65.7%	37.6%	28.7 %

Table E 6: Vacancy Times for IPOS and PIR with a Time Delay of 15 Minutes

Appendix F – IPOS as a Daylighting Device: Photosensor and Commissioning Tool

Building energy consumption in the U.S. is more than 40% of the total energy consumption of the country, which has led to a national focus on increased building systems energy efficiency and whole-building energy goals. For example, Executive Order 13514 mandates that all new federal facilities achieve net-zero energy by 2030. It is possible to cost effectively achieve net-zero energy in commercial construction, which translates into almost 50% energy savings over current code, as has been shown by examples such as NREL's Research Support Facility. This deep energy use reduction is only possible, though, when an emphasis is placed on daylighting and related electric lighting use reduction [22] to achieve more than 75% lighting energy savings versus an ASHRAE 90.1, 2007 code baseline [24, 26]²⁸. Unfortunately, current lighting control technologies and specification and commissioning practices often do not lead to realized energy savings [20].

A primary reason that lighting energy savings are rarely seen is the high implementation risk, the potential for installation details to cause highly variable results of some system components, in particular daylighting control. A recent field study by the Energy Center of Wisconsin [19] corroborates a similar field study performed by the Heschong Mahone Group [21] by showing that the average realization rate of daylighting systems is 50%. The earlier study uses corrected energy models for the percent savings baseline; the latter uses the amount of savings realized after re- and retro-commissioning, which could mean that different sources of error contribute to each study's results. Sources of the error include incorrect daylight modeling assumptions and calculation approaches, incorrect initial photosensor commissioning, and/or inadequacy of technology to track actual daylight contribution and to adapt over time to account for interior design changes. Regardless of the source, the message is clear: daylighting system energy savings are not being fully realized. For this reason, Target Stores informally use a 50% risk of realization (in other words, an energy savings de-rating factor) in their return on investment considerations, which leads them to reject daylighting as a feasible energy efficiency measure.

In order to achieve aggressive lighting savings, daylighting design and control issues need to be addressed. The design of façades and interiors for optimal daylighting saturation, as well as energy modeling accuracy²⁹ are well documented in other white

²⁸ The 75% lighting energy savings target is for the entire lighting system. This is typically possible only when the installed lighting power is reduced from code allowance, the daylighting design is well-considered, and the electric lights are controlled for daylight, occupancy, and occupant preference. The first study referenced shows that 75% lighting energy savings has been achieved at the whole building level on the NREL campus in Golden, CO; the second study shows that more than 60% energy savings has been achieved for a California office space while only using some of the aforementioned lighting energy saving strategies.

²⁹ Energy modeling accuracy was eliminated as a potential source of error in the Energy Center of Wisconsin [21]; therefore, the 57% risk of realization result can be attributed to installation and

papers and design guides, and do not contribute to the 50% realization rate cited. This white paper focuses on daylighting technology, installation, and commissioning issues and proposes an intelligent system that is easier to commission, and can adapt over time by responding to changing daylight conditions, building conditions, and occupant preference. Specifically, an image-based photocell with an open, software-based controller is suggested.

This solution is arrived at by first describing the current state of lighting controls, with an emphasis on daylighting response techniques, to show how 75% energy savings can be achieved. Second, requirements are given for a daylighting control system that (1) prevents current issues by addressing commissioning and illuminance mapping, and (2) maximizes the probability of realizing estimated lighting energy savings. Third, current daylighting commissioning and control technologies are grouped and compared to the previously outlined requirements. Lastly, IPOS is evaluated for its potential to meet the outlined requirements, and a brief roadmap is given for the steps needed to transition IPOS from an occupancy sensor to a multi-sensor, functioning as a daylighting (initial, re-, and retro-) commissioning tool and photosensor.

State of the Art of Lighting Control

Electric lighting energy use reduction is required by energy efficiency code requirements. For example, ASHRAE 90.1 2010, which will be referenced by most building codes in the coming decade, requires that lights be shut off when occupants are not present and within daylight zones. California's most recent Title 24 revisions take control requirements a step further by requiring daylighting in most spaces that can be top-lighted (i.e., lighted with skylights). These requirements will likely result in a steep increase in the penetration rate of daylighting control systems. In addition to the code requirements, the national trend is toward more sophisticated designs and systems. Currently, lighting control product specifications straddle the line of basic and sophisticated, or "smart." Smart controls are not needed to meet code requirements, but they have the potential for greater energy savings due to monitoring capabilities, ease of use when making minor system changes or full retrofits, and software-based building automation system integration. The most recent advancements in control systems have been in the modes of communication, system topology, and central control interface.

The trend of more aggressive code requirements is driven by national and state energy reduction goals; the trend toward smart control systems is primarily driven by manufacturer offerings and owner requests for system flexibility. The design community balances the performance interests and cost considerations, while the installer and commissioning agent attempt to align system operation with the project goals. All elements exist for deep lighting energy savings but gaps between design, commissioning and operation of smart lighting control systems result in an implementation success of 50%.

commissioning alone. A conservative 50% risk is then assumed to be the risk associated with photosensor technology limits in the remainder of this white paper.

To achieve lighting energy savings at the level of 75%, electric lighting must be off when it is not needed. Although this sounds obvious, the requirement extends well beyond the traditional description of need, which is described in code as turning off lights at night, if the building is not in use. A more aggressive description of “need” is that lights should be on, to the appropriate light level, or illuminance, only as required by an *occupant* performing a *task*, for the limited period of *time* and for the limited spatial *location* of that task. A limited-scope survey of common lighting control philosophies and associated technologies for low-energy buildings is presented in the following sections, in context of the idea of meeting occupant-task needs.

Occupancy Control

Occupancy control addresses the *occupant* variable in the lighting need definition presented previously. The systems discussed in the following sections control for the *time* and *location* aspects of occupancy, each to varying degrees.

Timers

Timers, the most straightforward lighting control technology, shut lights off after a pre-determined period of time (e.g., a room-specific switch that allows an occupant to override lights on for two hours) or recurrently, at a specific time of day (e.g., building-central time clock that coincides with typical occupancy schedules). Although timers are technologically sound and simple to specify and install, particularly for retrofits, they often miss opportunities for energy savings when a space is not occupied for parts of the scheduled on-time, or on holidays. In addition, central time clocks are not typically zone-specific. So although central timers partially address *time* of occupancy, they do not usually address *location*. Timers represent a current code baseline, where lights are off at night except for times when occupants override the timer for nighttime use of the space.

Occupancy Sensors

Occupancy sensors, a common lighting energy efficiency retrofit measure, turn lights on and off in response to occupancy. As presented in this report, traditional occupancy sensors detect motion or sound and turn lights on and off accordingly, with time delays or dead bands, to prevent rapid switching or false-offs. Despite the error checking mechanisms installed in most occupancy sensor systems, false-ons and false-offs are common, leading to occupant frustration and often system tampering or decommissioning. The lack of system intelligence can lead to *time*-based energy savings not being realized³⁰. If occupancy sensors are overridden, all potential energy savings (highly dependent on occupancy patterns, ranging from 10%-70%) can be lost.

The IPOS adds intelligence to typical occupancy sensor systems by more accurately detecting occupancy through image capture and analysis; with this technology the savings attributable to *time* of occupancy can be fully captured. Also, spatial awareness

³⁰ Timer-based control is included in the baseline for the IPOS (occupancy only) calculations of lighting energy savings in the final project report. Typical daytime occupancy patterns are added on, although typical dead band settings make the off-time low relative to actual space occupancy.

of an IPOS unit can lead to more aggressive energy savings than a spatially unaware occupancy sensor. In addition, a single IPOS unit has the potential to control lighting within many zones whereas traditional occupancy sensors that would need to be placed and commissioned in each zone. IPOS therefore addresses the *time* and *location* of occupancy.

Vacancy Sensors

Vacancy sensors are occupancy sensors that also address the *occupant* and *task* variables in the definition of lighting “need”. For example, a manual-on, automatic-off occupancy sensor is a vacancy sensor because the lights do not turn on automatically if the occupant does not need the lights for the task, such as walking through a space. The sensor technology is the same as for occupancy and vacancy sensors; the difference exists in the logic to turn the lights on³¹ or keep them off. An additional 30% lighting energy savings can be achieved through the use of a task-orientated occupancy sensor [18].

The key to this technology realizing deeper energy savings than an occupancy sensor is daylighting. If even a small amount of daylight is present in a space, through borrowed light or direct daylight source, occupants can use that light instead of the space’s electric light for some *tasks*. This is different than automatic daylighting control where a photosensor reduces already on electric lighting in response to daylight contribution.

Daylighting Control

Daylighting control addresses the *task* variable in the need-based lighting control definition. Although vacancy sensors address task needs, if an occupant does not turn off lights when daylight is present, task-based lighting energy savings are not fully realized. Use of vacancy sensors without daylight sensors results in only 50% of the potential energy savings [19].

Photosensors

Typical photosensors reduce electric lighting use based on available daylight. A system commonly consists of a photocell (the sensor that detects the quantity of daylight) and a controller that determines the appropriate response for the electric lights (e.g., on, off, or percent dim). A photocell is commonly assumed to read true illuminance, but typically reads a relative signal with respect to the amount of light on the sensor. The photosensor is typically set at a constant setpoint, which is meant to represent the illuminance needed for the most common task in the space.

A gap in potential versus realized energy savings exists with these systems because task variation in a space is not accounted for, and because the simple photosensor technology is not able to accurately translate light on its surface to a maintained annual illuminance at the workplane. Workarounds such as a sliding setpoint scheme exist, where the setpoint increases as more daylight reaches the photocell. This is meant to

³¹ IPOS works well with vacancy sensor logic because of the latency of IPOS with first detection is avoided since a switch always gives the first on signal.

compensate for the differing rates at which daylight increases on the ceiling versus on the workplane. Up to 50% energy savings can be seen from daylighting control during daylight hours for typical office spaces; however, it is more common to see less than 25%³² energy savings even in well-commissioned spaces because of workarounds and setpoints needed to ensure adequate *task* illuminance to maintain occupant comfort.

Direct Sun or Glare Detection

An extension of the task-based control provided by occupancy sensors is fenestration shading control. This type of building technology is often applied to reduce heat gain, but in the context of lighting, it can be applied to prevent glare in occupants' working zone, which would otherwise inhibit task performance. The common options for glare control include astronomical time clocks to change façade elements based on time of day, or exterior photosensors that detect the presence of direct sun.

The gap in this technology with respect to electric lighting energy savings is that the control schemes do not actually detect glare at the occupants' working zone. The direct sun position proxy for glare works well in many applications, but anecdotal evidence shows that a lack of glare control in buildings leads to overridden façade solutions (e.g., continuously closed blinds) and ultimately overridden daylighting control systems. While the complete loss of energy savings due to inadequate glare control cannot be attributed to the gap in sensor technology, appropriate façade and sensor solutions are needed to realize the potential energy savings.

System Topology

The sensor components described in the previous sections join with communication systems, and possibly higher-level logic devices, to make up a building's lighting control system. As previously stated, central systems such as a building-level time clock cannot fine tune on-time to maximize occupancy-related energy savings for each zone. Many current, digital lighting control systems are spatially distributed to address this gap. Each room is set up with a subsystem of sensors and actuators/switches, and sometimes even fixture-level dimming control, to maximize energy savings for the specific tasks and time of use for each space. The drawback with this setup is the potential for complicated maintenance and increased system costs due to the large number of devices.

Commissioning

Basic commissioning services for a lighting control system typically include checking the schedules for time clocks, testing occupancy controls for false-ons, and tuning photosensor setpoints using a handheld illuminance sensor at the workplane³³. This work is commonly performed in a week's time or less, meaning that only a certain number of occupancy and daylight conditions can be tested. Ongoing commissioning or

³² A 25% loss is implied from [19]; only 25% savings could be realized due to re-commission therefore the remainder of the 50% average effectiveness is assumed to be lost because of technology limitations.

³³ Setpoint tuning is typically performed by the lighting control system installer or manufacturer as part of the system setup but is tied to commissioning scope since tuning continues as the commissioning agent gives feedback about system performance.

retro-commissioning can be performed to check the settings with respect to design intent. This is typically accomplished using light loggers that are placed near sample light fixtures. The loggers detect occupancy within a limited zone and they detect light switching, but not dimming. The logger data must be collected manually with current logger systems, and then processed and analyzed by a lighting controls expert to understand the level of performance of the lighting control system. Since this level of effort is not usually included in commissioning scopes of work, only 25% of the potential lighting energy savings are realized [19].

Through rigorous design considerations, control system specification, and extensive initial and periodic ongoing commissioning NREL's RSF achieved 75% lighting energy savings [24]. While this shows potential for deep lighting energy savings, it is not the norm. Disjointed sensor systems and proxy measurements for real lighting quantities result in lost energy savings from the potential for a given occupancy schedule and variance of task types.

The BPA funded IPOS project addressed the gap in occupancy control. The remainder of this report will explore the potential for IPOS to address the gaps in daylighting control, simple system topology, initial and ongoing commissioning, and ultimately, fully-realized electric lighting energy savings.

Goals and Requirements for Daylighting Control Systems

The previous section focused on the big picture of the state of the art for lighting control for energy efficiency. This section narrows in on daylighting control potential for energy savings. To achieve the 50% daylighting energy savings target, several issues need to be addressed. Approximately half of the issues include good daylighting design and basic control implementation, and the other half requires a change in control industry best practice to realize and maintain optimized operation. The latter half, which is often not achieved, can again be broken into two sources of error relative to energy savings potential:

1. *Commissioning practices.* In a 2004 survey of four case studies with daylighting control, all projects suffered from implementation failure of some sort [25]. Half of the projects were under-dimming, resulting in lower than expected energy savings. All field survey studies cited in this white paper list a number of reasons for implementation failure, which include: setpoints were set too high likely because the commissioning agents wanted to be conservative to mitigate risk of occupant complaints; the system was commissioned during non-optimal daylight conditions, resulting in non-optimal setpoints; daylighting zones are too large, with the darkest regions driving non-optimal setpoints; and disruptive dead band settings causing systems to be overridden. One approach to address this source of error is to create a tool that better guides commissioning agents in initial setup, re-commissioning, and/or retro-commissioning. Another option is to create a more intelligent daylighting control system that can address these issues through continuous monitoring and adjustment. Both paths will be discussed in the system goal outline.

2. *Technology design.* As described above, photosensors are meant to maintain a consistent illuminance at the workplane, but a typical sensor's location on the ceiling, and spatial and spectral sensitivity to light, prevent it from being able to accurately do so. For retrofit scenarios, these two sources of error (commissioning practices and technology design) are distinct since only commissioning practices are likely to be addressed in the field. For new construction, though, a better photosensor design could address commissioning practice error by providing more accurate and robust information about the space conditions so that commissioning agents can limit the use of setpoint safety factors.

These two paths for improved daylighting energy performance will allow daylighting control systems to approach the current benchmark of 50% lighting energy savings. Another perspective that should be given before defining general goals is that of an optimal daylighting control system (i.e., raising the benchmark higher than 50% lighting energy savings). An optimal system would bring together real-time information on occupants at specific locations, performing specific tasks, with daylight availability to determine system settings that optimize the daylighting conditions. Input for this optimization problem could also include occupant preference, whole-building energy use status, demand response needs, or other competing factors. In this vision for an optimal daylighting control system, all daylighting connected systems would be communicating and changing in real-time to provide the best-available options for energy savings and comfort. Also, the input prioritization should be the focus of commissioning, (for example, giving real-time occupant preferences priority over an illuminance or demand response signal) not the manual tweaking of settings that lock current photosensor systems into inherently non-optimized settings for the life of the building.

The following list outlines goals for a commissioning tool and/or daylighting control system that could consistently produce deep electric lighting energy savings and maintain occupant comfort to prevent system overrides. The system setup and commissioning process is used as a frame of reference

- **Short initial commissioning time (or automated commissioning process).** Commissioning scope is typically 1%-2% of a new commercial building's design and construction budget. If that budget is distributed according to potential energy impact, the result is approximately one week for initial daylighting system commissioning. For a typical 100,000 ft² office building, this would break down to 15 minutes per zone. This limited time is enough to confirm that electric lighting fixtures are correctly mapped to control points, and to tweak the daylighting setpoints in each daylighting zone; it typically does not leave enough time for optimized annual daylight setting selection, as shown through the referenced case studies. It is not realistic for commissioning timeframes to change significantly because installers and commissioning agents need to execute most work on a daylighting system after furniture setup but before occupants arrive. Additionally, successful commissioning currently requires highly skilled experts

with extensive experience and training. In order to become widely deployed, lighting control systems need to be “plug-and-play,” with automatic initial and ongoing commissioning. If any human interaction is required, it should be very simple and easy, described by a one-page procedure, rather than weeks or years of specialized training. For these reasons, a first goal for an ideal daylighting system is to allow for a short initial commissioning time where most of the setup (electric fixture mapping) and tuning (daylight setpoint selection) work is performed automatically. The technology requirements for such a goal include being able to accurately track workplane illuminance, automatically map electric lighting physical location to a system control point, and then adapt settings or control algorithms over time as needed.

- **High initial commissioning accuracy:** As implied by the first system goal, the initial setpoint for maintained electric lighting illuminance at the workplane must be set automatically so that it is aggressive enough to realize the predicted energy savings but buffered enough so that occupants do not consciously notice the daylighting control cycles. The initial setup period is an important phase for setting occupant expectations for daylight dimming or switching cycles. To achieve this initial setting goal, a sensor must have specific knowledge about its environment such as interior surface properties and likely weather conditions within the initial commissioning period and a typical year. The latter information can feed into control algorithms that adapt dimming rates and on/off cycling depending on a variety of factors other than instantaneous workplane illuminance. The related technology requirements are for the system to accurately track illuminance at the workplane and understand weather conditions.
- **Initial commissioning flexibility:** In current practice, initial commissioning time is often reduced by using a test space to hone in on the appropriate setpoint and then applying that setpoint across similar space types (or by using an open loop control system as described in a following section). But, the ideal commissioning practice would be space-specific. Different space configuration factors with respect to exterior building façade elements and/or exterior landscape mean that energy savings or comfort can be lost if each space is not considered independently. The technology requirements to meet this goal are the same as the previous two goals since the goal translates to a fast commission process with high accuracy for each space type. Spatial awareness of interior conditions and lighting fixture location is necessary.
- **Ongoing commissioning to maintain energy savings and illuminance with minor space changes:** Assuming initial setup happens accurately and in a cost-effective way, the path to deep energy savings has been etched. But, it is possible and likely that throughout the course of a building’s operations, the surfaces from which light is reflected onto a sensor will change, which will impact the maintained workplane illuminance and resulting energy savings. A complete daylighting system would account for this time-based variable and counteract it through adaptive setpoint control. The technology requirement includes accurate workplane illuminance detection, spatial awareness of interior surfaces and/or

the ability to map and control electric lighting fixtures, with no user interaction required.

- **Ongoing commissioning to maintain energy savings and illuminance with respect to occupant feedback:** While energy savings is the focus of most daylighting control applications, occupant comfort should be considered; buildings are for people and people will adapt the building control systems to meet their task needs. To ensure that systems do not get overridden by unhappy occupants and to adapt setpoints over time to take advantage of occupant preferences for less light, a complete daylighting control system would accept and adapt to occupant preferences to a reasonable degree. The technology requirement for this goal, in addition to the previous requirement given, is to openly communicate and accept/provide information from/to occupants and the other building control systems. This goal extends beyond those that solve the current 50% daylighting-related energy savings benchmark gap and sets forth an optimized way to control daylighting that includes occupant feedback to fine tune setpoints for specific locations and task needs, and to respond in an occupant-accepted way to demand response events.
- **Simple verification and retro-commissioning:** For retrofit scenarios in which façade elements (i.e., the daylighting design) and the electric system remain intact but a lighting control energy efficiency measure is implemented, it is common to install temporary monitoring equipment to determine:
 - Lighting on/off pattern
 - Occupancy patterns over a test period, resulting in need-based percent on-time for individual fixtures
 - Lighting quantity, resulting in average workplane illuminance

Goals for such a monitoring system include minimal equipment cost and setup time, and reduced data analysis time. The technology requirements are to log illuminance at the workplane, determine electric lighting location and on/off status, automatically perform analysis of the results, and to communicate these results with a remotely located commissioning agent. Essentially, the requirements of a stand-alone verification and commissioning tool are the same as an ideal photosensor system.

- **Dual purpose devices:** Although this is not the focus of this section, it is worth mentioning that a complete daylighting control device would have synergy with other building systems to reduce cost of materials and installation. Example synergies are:
 - Occupancy sensors, where one device can be placed in a lighting zone or room to accomplish daylight and occupancy detection and control
 - Security sensor, where some of the occupancy control devices can be used for security purposes

- Verification and retro-commissioning tool; use necessary sensor distributions required for daily daylight operation for performance monitoring as well, as described in the previous goal

The technology requirement for this goal, not already listed in other goal descriptions is sensor mounting location flexibility. Each potentially paired device has mounting location constraints and so an ideal photosensor system would function under these differing requirements.

Through the process of defining the goals, the following technology requirements for an ideal daylighting control system, which functions as an ideal verification and retro-commissioning tool, are to:

- Measure illuminance at the workplane
- Understand interior, spatial conditions
- Discern electric lighting location
- Function at a variety of mounting locations
- Collect weather information
- Control lights to optimize occupant comfort and energy savings (not a requirement for a verification tool)
- Communicate using an open protocol
- Automatically determine and apply optimal system settings over time

Daylighting Control Types and Gaps

This section groups and then compares existing daylighting control technologies to the ideal daylighting control system requirements and goals described in the previous section.

To start, some basic terminology as described in [23]:

- **Photocell or sensor:** To this point, the term *sensor* has been used to discuss the measurement point on the ceiling. A more descriptive term for the system component is *photocell*. This is the system component that detects the relative quantity of light at a point on the ceiling and turns that into an electrical signal. The signal is not spatially aware and, in most systems, it does not measure true illuminance. It simply provides a signal to the controller (e.g., Table F 1, example 1).
- **Controller:** The controller is the component that determines the status of the lights by comparing the information received by the photocell to the commissioned settings. The controller sends a signal to the light fixture/ballast or sometimes serves as the actuator.
- **Photosensor:** A photosensor is the photocell or sensor and controller combined.





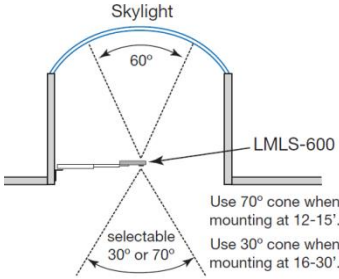
- **Commissioning tool (not described by [23]):** A commissioning tool is the peripheral component of a daylighting control that is required to set up the photosensor. In incumbent daylighting control systems, the commissioning tool is typically part of the photosensor as a dial or button that allows setpoint adjustment. In more recent daylighting control systems, this can be a hand-held device that communicates with individual controllers or a web-based interface to a central controller.

Rather than comparing specific lighting control products to the requirements and goals, common products are grouped into categories for comparison:

- **Illuminance meter:** An illuminance meter is a critical component of incumbent daylighting systems, although not actually part of the system. In order for a commissioning agent to set up a system, the workplane illuminance must be checked as the commissioning tool is used to lock-in setpoints. An illuminance meter as referred to here is a mobile, hand-held device that has a cosine-weighted spatial response to light and is spectrally sensitive based on the human sensitivity function.
- **Light logger:** A verification or retro-commissioning device that detects electric lighting status and occupancy (e.g., Table F 1, example 2). These are the most commonly used devices for energy efficiency measure verification and retro-commissioning.
- **Open-loop photocell:** A control system philosophy that consists of one photocell, typically located on the roof of a building that only looks at daylight contribution. An advantage of this system is that there is one device to maintain and setup. Typically, only one setpoint is used for many spaces although some systems allow for variable setpoints. Another advantage is that the photosensor is not accessible by occupants to override. On the other hand, this system type has a lower potential daylight savings if many unique spaces exist because the option for multiple setpoints does not exist. Also, the occupant is not “in-the-loop” in the sense that their actions inside the room do not impact electric lighting output, which can impact energy savings and comfort. This type of photosensor cannot serve as a multi-sensor.
- **Closed-loop photocell:** A control system philosophy that consists of at least one photocell per space, located on the ceiling that inherently takes into account daylight and electric lighting contributions. An advantage of this system is higher potential for daylight savings if each space is fine-tuned to its specific interior and exterior environment. It can address different occupant task needs in different zones. Conversely, a closed loop system has many devices to commission and maintain, and may need re-commissioning if the interior space changes in layout or color.
- **Dual-loop photocell:** As the name suggests, this is a combined open- and closed-loop approach where the innovation is in a controller that compares the ratio between the two signals to determine if a setpoint adjustment should be

made or if one photosensor should be followed versus the other (e.g., Table F 1, example 3). The benefit of the redundant system is added reliability in case of sensor failure and the driving reason for the design is improved illuminance tracking over time as interior conditions change. Added installation and commissioning time/cost and limited commercial product availability currently prevents this system type from being widely used.

- **Fixture-mounted photocell:** An extension of a closed-loop system, fixture mounted photocells give an inherent one-to-one mapping of electric lighting contribution to the daylight zone. In an ideal setup, this system can lead to high daylight savings related to occupant preferences and daylight contribution differences throughout a floor plate. This system type is not widely used because many devices are required to maintain and commission it, and electric lighting fixture specification must tie in directly with the control system specification.
- **Closed-loop image-based sensor:** This system type is similar to a closed-loop photocell, except that an image-based sensor, or camera, captures spatially coherent lighting information (e.g., Table F 1, example 4). The advantage of such a system is that information about occupancy, fenestration location, electric lighting fixture location, and workplane location can potentially be determined, which sets up an infrastructure to meet the ideal daylighting control system requirements outlined in the Goals and Requirements for Daylighting Control Systems Section. The current disadvantage is that such systems are not commercially available and lead to concerns about invasions of privacy. It should be noted that images captured by IPOS are removed from memory after analysis.
- **Analog controller:** A controller that uses simple 0-10 volt circuitry to accept an analog signal from a photosensor and provide an analog signal to a ballast or other control system component.
- **Digital controller:** A controller that uses digital circuitry and specific communication protocol to allow for more complex translation of controller input, such as a photocell signal, to photosensor output. This system type offers increased flexibility of control algorithms and setting options versus analog controllers but can lead to system compatibility issues not often encountered with analog systems.
- **Software-based controller:** A software-based controller is an extension of a digital controller, offering added system setting flexibility (e.g., Table F 1, example 5). Such a system exposes controller attributes to an installer and commissioning agent, allowing for a system to be quickly and remotely optimized over time.

Example Technologies	Image	Description	Picture Credit and More Information
(1) Douglas Lighting Controls photocell and controller		Photocell that sends a data signal to the controller	http://www.douglaslightingcontrol.com/products/dialog/wps-3711-interior-photo-sensor
		Controller that accepts the signal, determines the appropriate status of the lights based on manually entered settings, and then sends a signal to control the lights/relay	
(2) WattStopper light logger		Occupancy and light logger that is battery operated and stores data for manual retrieval	http://www.wattstopper.com/products/occupancy-vacancy-sensors/accessories/it-200.aspx#.Ughud9J-BNQ
(3) WattStopper dual loop Photosensor		Dual-sided controller housing two photocells and partial control logic. Full functionality requires integration with a larger digital lighting control system	http://www.wattstopper.com/products/digital-lighting-management/daylighting-controls/lmls-600.aspx#.UghvbdJ-BNQ
		Mounting instructions that show the open loop component facing the skylight and the closed loop component facing the room	


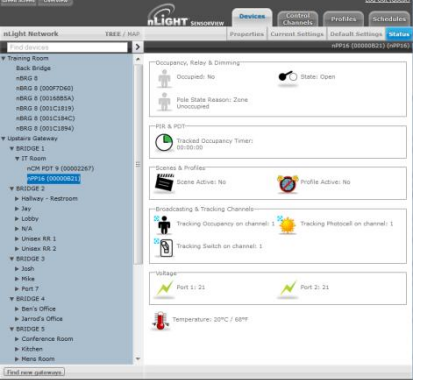
(4) IPOS and Fabriq image-based Sensor commissioning tool		Research-phase photosensor and commissioning tool. One image-based sensor is placed at the workplane during commissioning to identify lighting fixture location and address. Another image-based sensor is permanently located on the wall to control for occupancy and daylight (preliminary daylight control)	N/A
(5) Acuity Brands nLight software interface		Sample user interface that shows the capability to view device settings and make setpoint changes from any computer/device that can communicate with the central lighting control server	http://docs.nlightcontrols.com/using-sensorview/view-device-status

Table F 1: Example Technology Descriptions

The following tables evaluate each product category’s ability to meet the ideal daylighting system requirements outlined in the Goals and Requirements for Daylighting Control Systems Section. The purpose of the table is to display the potential for each product type to meet the requirements. The table lists “yes” when the existing technology already meets the requirement, “potentially” when the current technology could meet the requirement, and “no” when its fundamental design prevents it from meeting the requirement. The tables are grouped by daylighting control system components.

Table F 2 shows that both an illuminance meter and light logger are needed to perform even the basic tasks of commissioning, verification, and retro-commissioning. Neither of the commission tool categories offers robust commissioning functionality.

Commissioning System Requirements	<i>Is there potential for the technology to meet the requirement?</i>	
	Light Logger	Illuminance Meter
Measure Illuminance at the Workplane	no	yes
Understand Interior, Spatial Conditions	no	no
Understand Electric Lighting Location	yes	no
Function at a Variety of Mounting Locations	no	no
Collect Weather Information	no	no

Table F 2: Commissioning Tool Category Comparison to Ideal Daylighting System Requirements

Table F 3 shows that a closed loop, image-based photocell has the highest potential of available technologies to meet an ideal daylighting control system specification.

Sensor Requirements	<i>Is there potential for the technology to meet the requirement?</i>				
	Open Loop Photocell	Closed Loop Photocell	Dual Loop Photocell	Fixture-Mounted Photocell	Closed Loop Image-Based
Measure Illuminance at the Workplane	no	potentially	potentially	no	potentially
Understand Interior, Spatial Conditions	no	no	no	no	yes
Understand Electric Lighting Location	no	no	no	yes	yes
Function at a Variety of Mounting Locations	yes	potentially	potentially	no	no
Collect Weather Information	yes	no	yes	no	yes

Table F 3: Sensor Category Comparison to Ideal Daylighting System Requirements

Table F 4 shows that a software-based controller is needed to meet the intelligence and flexibility requirements of an ideal lighting control system as outlined in this whitepaper.

Controller Requirements	Dimming	On/Off	Analog	Digital	Software-Based
Collect Weather Information			no	no	yes
Control Lights To Optimize Occupant Comfort and Energy Savings	yes	no	no	yes	yes
Communicate Using an Open Protocol	yes	yes	yes	potentially	yes
Automatically Adapt Settings over Time	yes	yes	no	no	yes

Table F 4: Controller Category Comparison to Ideal Daylighting System Requirements

IPOS Daylighting-Related Feature Description

The vision for an ideal lighting control system outlined in this whitepaper substantiates IPOS as a potential baseline technology for future photosensor and/or verification and retro-commissioning products versus incumbent technologies. To further investigate the potential for IPOS to meet outlined goals and requirements, current IPOS capabilities are described in this section. More specific information on the steps needed to take IPOS from its current state to an optimized daylighting control or retro-commissioning device is given in the following section on Roadmap for IPOS Daylighting Commissioning and Control Technology Development.

- Measure illuminance at the workplane:** The IPOS sensor camera currently used in the demonstration prototype has a field of view of 45 degrees. The requirements for determining illuminance are that the workplane location and reflectance are known, that the location is within the sensor coverage area, that the surface is diffuse, and that portion of the image that contains workplane information is not over- or underexposed. The first two requirements can either be determined automatically (not current feature) or through manual input during setup/commissioning. If the workplane location is known, the pixel values created from an image-based sensor can be tagged as workplane pixels and analyzed for illuminance. Ensuring that the workplane is in the sensor's coverage area is simply a matter of camera specification. The coverage area depends on this field of view. The field of view can be increased if needed with the use of a different camera with a larger field of view, thus achieving a greater coverage area. Regarding the third requirement, most workplane surfaces are diffuse. Lastly, the camera used in the IPOS prototype can be set on each image capture to expose for various conditions. It is possible, but not currently implemented, that the camera be controlled to capture a range of exposures on each image capture to ensure that fidelity in light distribution is maintained at the workplane from the sensor's point of view.
- Understand interior, spatial conditions and discern electric lighting location:** The current IPOS driving software allows specific regions of an image to be analyzed. Algorithms to detect electric lighting regions have been considered but not implemented or verified. Regions can be manually selected in

the current prototype, although certain building features such as workplane location, electric lighting, and fenestration would need to be automatically detected to meet the goal of short initial commissioning time. A currently implemented advantage over incumbent technologies is the reduction in the number of sensors needed for the same area of coverage. This efficiency can be achieved with a combination of multiple virtual zones implemented in a single sensor, and/or an increased field of view of the camera.

- **Function at a variety of mounting locations:** For daylighting harvesting only, mounting location can be any, as long as a view of the workplane, electric lighting fixtures, and possible fenestration is maintained. This difficulty of this requirement depends on the field of view of the camera. A larger field of view makes the mounting height more flexible. When occupancy detection is desired along with daylighting control, mounting locations cannot be at heights that make people or faces unrecognizable. Typical mounting heights should not exceed 8-10 feet. It is possible and likely that the daylighting and occupancy sensing requirements will conflict, but how much is currently unknown. This conflict could be addressed by using separate cameras for daylighting and for occupancy sensing or by using different people recognition algorithms based on mounting height. In the latter option, mounting height would become an input determined at the time of commissioning.
- **Collect weather information and communicate using an open protocol:** The wireless communication protocol used by IPOS would allow for weather information to be collected from the internet or local weather stations, assuming firewall restrictions of a specific building do not prevent this open setup. The most important weather-related information to collect is input for cloud cover predictions as well as exterior vertical and horizontal illuminance/irradiation. The information would be an input into a more robust dimming control algorithm that would, for example, smooth dimming cycles on partly cloudy days, preventing occupant frustration with frequently cycling light levels.
- **Control lights to optimize occupant comfort and energy savings** (not a requirement for a commissioning/verification tool): The open software platform used by IPOS allows for extensive flexibility in accepting input and tailoring control algorithms to optimize the output. Currently, the power levels for lighting control are configured to be discrete (the number of power levels is user-configurable) or continuous, changing in time-delayed increments to prevent rapid cycling of the lights. Additional control points in the current algorithms would be necessary for a daylighting system robust enough to respond to complex input such as occupant feedback and weather conditions.
- **Automatically determine and apply optimal system settings over time:** The storage capability of IPOS would allow for historic setpoint and surface luminance measurements to be saved for comparison to current conditions. This comparison, along with weather information and other input sets the foundation for adaptive control algorithms. An adaptive algorithm has not been applied or even detailed for the current IPOS prototype.

A barrier to using IPOS as a base technology is locating the sensor to see all lights and adequate occupancy view. This, along with further investigation of IPOS' capability to accurately track illuminance and adapt to changing interior conditions over time are the primary research hurdles for evolving the current prototype to a base daylighting control technology.

Roadmap for IPOS Daylighting Commissioning and Control Technology Development

The IPOS prototype has potential for development as an integrated daylighting harvester/occupancy sensor, capable of modulating light loads in the sensor's field of view or in multiple virtual zones for more localized and independent daylighting and occupancy control. In addition, the IPOS prototype and/or software could be used as a continuous retro-commissioning device.

This section references the daylighting-related use cases detailed in Section 5 and prioritizes the research needed to most efficiently transition the IPOS prototype and software to a daylighting technology, actively saving energy in the BPA region. This roadmap outline focuses on lighting energy savings related to daylighting; however, crossovers to general lighting control energy savings are listed.

The end goal of this roadmap is a prototype for a daylighting control and commissioning devices outlined in this paper that can enable 75% lighting energy over current code to be consistently achieved. The roadmap is divided into four steps that represent short to longer-term research:

Step 1 (short term): Measurement of energy saving potential and verification of energy saving results using existing, local cameras and IPOS software

Step 2 (short term): Measurement of energy saving potential and verification of energy saving results using newly installed IPOS hardware/firmware as well as IPOS software

Step 3 (longer term): For the location(s) where IPOS has been deployed in step 2, and for which energy savings potential has been determined, leave the IPOS hardware in place and retrofit lamps and ballasts for integrated IPOS control

Step 4 (longer term): For the location(s) where IPOS has been transitioned into a control device in step 3, enhance the control algorithms based on lessons learned in step 3 with the end goal of maintaining energy savings and improving occupant comfort for one year

A prototype developed at the end of step 4 would not be the ideal control device presented in this white paper that incorporates weather predictions and accepts occupant preferences, rather it would be a device that meets the immediate need of preventing implementation failures due to the limitations in illuminance tracking and commissioning inherent with the incumbent technology. Each time-sequenced step in

the roadmap follows that same process of performing initial research, demonstration and then commercialization.

Step 1 (short term) - Measurement of energy savings potential and verification of energy saving results using local camera and IPOS software

Use case and outcome: This step combines the IPOS project report use cases of Occupancy and Event Logger for Occupancy Analysis, and Light Logging and Sub-Metering. Specifically, images from existing cameras could be processed using IPOS software to determine the delta between occupancy, daylight availability, and lighting energy use in a space type with anecdotal potential for energy savings such as a continuously lit parking garage. The purpose of step 1 is to take advantage of existing imaging hardware for near-term energy savings assessment.

Stakeholders: Organizations such as utilities need to understand energy savings potential and realized energy savings after energy efficiency upgrades without installing expensive metering equipment for temporary use. Likewise, ESCOs and building owners looking to make energy efficiency upgrades across portfolios of buildings need a way to sample lighting energy saving potential and results without installing light loggers on every fixture in a building. Current technology used for logging light and occupancy status for measurement and verification activities require a direct connection to the device to download results. This creates a potentially expensive scenario if data is lost or if loggers are tampered with during the collection period. A remote connection allows for substantiation of data quality during the monitoring period. Additionally, light loggers cannot measure partial load reduction for measures such as daylighting, requiring the use of submeters or scientific-grade monitoring equipment. The current solution to the cost and practicality gap of existing monitoring equipment is to use estimates or modeling to test the efficacy of rebate programs and portfolio efficiency upgrades. These solutions will not suffice to capture the energy savings losses inherent in current commissioning practice and technology shortfalls.

Preliminary research needs:

- Develop occupancy training sets for ceiling or high side-mounted sensors. Test ability for IPOS to determine lighting status from ROIs for a variety of existing camera locations (see Occupancy and Event Logger, Occupancy Analysis use case in the main report).
- Increase robustness of light status algorithms based on test results.
- Determine to what extent inexpensive web cameras can be gain-controlled to produce properly exposed images that discern pixel values at the workplane in all possible working luminous environments.

Step taken toward end goal (see the IPOS Daylighting-Related Feature Description section):

- Understand interior, spatial conditions and discern electric lighting location.

- Function at a variety of mounting locations.

Potential barriers: Restrictions might be placed on the use of images from another system such as security cameras, preventing their use for light and occupancy analysis. To mitigate this risk, identify a demonstration partner during the research phase that allows the use of security system images and to demonstrate secure access and use of secondary system images. Another risk in step 1 is that low illuminance conditions and/or non-controllable camera settings could result in inaccurate output from existing occupancy and light logging algorithms. An initial test will be performed to characterize the risk of using typical security cameras before seeking a demonstration partner.

Demonstration options: A call for a demonstration partner interested in retrofitting a subset of parking garages for bi-level occupancy controls could be released (pair with an LED fixture retrofit to ensure controllability). A partner would be selected that can provide access to images from existing security cameras for lighting and occupancy logging.

Licensing considerations: In this step, NREL would analyze the images using IPOS software to allow for tandem research and demonstration. No direct licensing considerations.

Commercialization partners: Building data analytics companies such as FirstFuel. Step 1 should require that commercialization partners be sought out so that a subsequent demonstration could take NREL out of the loop and allow for a third-party to license and incorporate the algorithms into their analysis software.

Step 2 (short term) - Measurement of energy saving potential and verification of energy saving results using installed IPOS hardware/firmware as well as IPOS software

The research needed for step 2 is the development of a weather-proof enclosure or system. The attributes of step 1 remain the same but the stakeholder shifts to those that have a project that does not already have imaging devices onsite or that cannot share the images that are collected.

Step 3 (longer term) - For the location(s) where IPOS has been deployed in step 2, and for which energy savings potential has been determined, leave the IPOS hardware in place and retrofit lamps and ballasts for integrated IPOS control.

Use case and outcome: This step relates to the IPOS project report use cases of Daylight Harvesting and Control, and Occupancy and Event Logger and Occupancy Analysis and Light logging and Sub-Metering. One outcome would be to enhance the occupancy and light status analysis algorithms and output, requiring less human-analysis such as would be provided by NREL in step 1 and 2. A second outcome would be to demonstrate the potential for ease and accuracy of commissioning a daylighting system that is spatially aware.

Stakeholders: Owners, utilities, and commissioning agents currently lack a smooth transition between showing measured lighting energy saving potential (step 1) and a properly functioning lighting control system. The transition can be aided by using the energy savings logging equipment to also guide commissioning activities. Owners and utilities benefit because realized energy savings will better align with predictions if commissioning error is removed. Commissioning agents benefit because specialized training will not be required for lighting commissioning and more attention can be given to the commissioning of more complex building control systems.

Preliminary research needs:

- Increase robustness of the occupancy control algorithm to prevent false-ons during daylight control (see the Daylighting use case in the main report).
- Develop and test workplane illuminance correlation to pixel values under a variety of conditions.
- Develop initial auto-commissioning algorithms that select an initial daylight setpoint based on measurements (or more accurate proxy) of workplane illuminance and verify electric lighting assignment/zoning.

Step taken toward end goal (see the IPOS Daylighting-Related Feature Description section):

- Measure illuminance at the workplane.

Potential barriers: The demonstration sites selected in step 2 might not be able to implement the lighting control measures to transition from a measurement scenario to a control scenario.

Demonstration options: In the event that the sites used for step 2 are not good candidates for the transition to a control scenario, review locations selected for step 1 as an alternative where existing camera hardware and controllable ballasts can be leveraged with IPOS software and installed gateways for communication between IPOS and the existing system.

Licensing considerations: In this step, NREL would seek out demonstration partners such as lighting control companies that use a compatible wireless communication protocol to demonstrate the transition from energy saving potential monitoring to energy efficiency measure implementation (using the same sensor hardware). It is possible that a blurred boundary between IPOS and the control system requires that the IPOS software be licensed by the control company.

Commercialization partners: Lighting control product manufacturers that offer retrofit solutions such as WattStopper or Leviton.

Step 4 (longer term) - For the location(s) where IPOS has been transitioned into a control device in step 3, enhance the control algorithms based on lessons learned in step 3 with the end goal of maintaining energy savings and improving occupant comfort for one year.

Use case and outcome: This step relates to the IPOS project report use cases of Daylight Harvesting and Control. While step 3 focuses on ease and accuracy of commissioning, step 4 focuses on maintained energy savings over time.

Stakeholders: Building owners and operators, and re-commissioning agents. Building owners often pay for daylighting control systems that are overridden or decommissioned due to their inaccurate control over time. The re-commissioning agent must have expertise in monitoring lighting control systems in order to accurately assess the source of the control issue. An ongoing commissioning algorithm will save owners money by preventing system failures in the first place and can aid re-commissioning work by providing the information necessary to quickly and easily assess the daylighting control behavior.

Preliminary research needs:

- Develop ongoing commissioning algorithms using the existing illuminance and area of interest features.
- Enhance self-training algorithms for excluding false-ons when noticed by a re-commissioning agent or by the sensor (Occupancy and Event Logger, Occupancy Analysis use case, Observation Numbers 4a and 4b).

Step taken toward end goal (see the IPOS Daylighting-Related Feature Description section):

- Automatically determine and apply optimal system settings over time.

Potential barriers: Technology barriers such as limitations with the IPOS camera may persist in step 4 since the premise of the roadmap is that the same technology installed in step 1 will be used through step 4. Features such as the camera lens, view angle, and gain could prohibit full demonstration of ongoing commissioning algorithms.

Demonstration options: In step 4, a site that allows engagement with the occupants will be necessary to determine occupant acceptance of the occupancy and daylight dimming sequences.

Licensing considerations: In this step, the licensing considerations would be an extension of those in step 3 since the involved parties and equipment would remain the same.

Commercialization partners: Lighting control product manufacturers such as WattStopper or Sylvania.

This roadmap outline presents an example path that progressively works toward a robust daylighting control and setup tool. The value of working toward a comprehensive tool is that a common device used for multiple purposes can reduce cost, increase familiarity in the industry to reduce the need for experts in each aspect of daylighting commissioning and control.

While the roadmap does give a path toward this end, it does not address the needs for an ideal tool of weather collection and occupant feedback. These needs are both in response to the identified gap in current daylighting control systems of occupant acceptance.

Accepting and processing third-party information that impacts occupant comfort could further enhance a combined daylighting control and commissioning tool but is not crucial to a more immediate improvement of the state of daylighting control commissioning and realized energy savings. They can therefore be considered longer-term research needs. An additional long-term research need is to pair the daylight and occupancy functions with other building sensing needs.

Appendix G – IPOS Image Acquisition Considerations, and Individual Detector and Assessment Functions Accuracy

Image Acquisition Considerations

The current image acquisition function consists of a script that collects frame captures from the camera sensor and stores the images in circular buffers in the shared memory area of the prototype. The images are processed by the detectors and the luminance estimation functions.

To ensure accuracy, the detector functions require that the images are correctly exposed and have balanced contrast. Conversely, the luminance estimation function requires images without exposure correction, to allow capture of a higher dynamic range. Because of these competing requirements, a single set of images was not sufficient for the prototype. The script uses Linux video driver controls to periodically drive the camera sensor into two states:

- An auto-gain state for generating correctly exposed images; these images were used for motion, face and people detection.
- An auto-gain disabled state in which the camera generates images as actually picked up at the sensor³⁴ and without manipulations, for luminance assessment.

This continuous switching between the two gain modalities necessitates the introduction of a several second image processing delay. This delay is required to accommodate the transition of the camera into the new state and to wait for the sensor to stabilize and internal buffers to be overwritten. Additional delays occur during camera setup for image capture, for capturing the images and for saving the frames to files. In the current prototype implementation these latencies have an impact on first detection of about 15-20 seconds.

Potential latency improvements may occur by collecting only a single set of images with auto-gain disabled, and letting the detector functions correct the exposure upfront according to the image illuminance. This method, however, puts an additional computational burden on the detectors. Other actions for improving latency would be to experiment with different camera models or refrain from saving the frames as files and use shared in-memory storage instead.

A recommendation would be to use IPOS as a vacancy sensor, i.e. manual-on, automatic-off lighting control strategy.

³⁴ Except for a fixed gain factor. Dark environments require a higher gain, and bright environments require a lower gain. In our prototype demonstration we employed a single fixed gain factor.

Individual Detector Accuracy

Motion

The motion detection function uses frame subtraction to extract motion information from images. Accuracy depends on the frequency at which image frames are collected, the extent of occupant motion, and variations in pixel brightness (not due to motion) from frame to frame. Pixel brightness variations can occur because of sudden lighting conditions not related to motion, and/or because of sensor noise. Both influence accuracy and sensitivity. We employed user-modifiable thresholds for calibration of the detectors (see discussion in Section 3.4).

Face and People

Both the face and people detector functions use algorithms available from the OpenCV library. In particular, the face detector function uses the Haar Cascade method, and the people detection function use the HOG (histogram of oriented gradients) method [7]. Each algorithm uses training sets representing the knowledge base needed to assess face or people presence in the image³⁵. We used generic frontal face and standing people training sets available from the OpenCV library in our prototype demonstration. Detection rates with those sets is estimated generally at 40-70% depending on subject size (i.e., relative distance from the camera), orientation, lighting conditions, image quality, and fixed objects present in the image. There is potential for detection rate improvements of the face/people detector functions by creating custom training sets for the specific environments to be monitored and by using multiple training sets in the algorithms. For example, the face detector accuracy could be potentially improved by having the prototype use multiple training sets representing knowledge of frontal faces, faces seen laterally, heads seen from the back, faces of people wearing eyeglasses, sitting rather than standing, etc. However, modification, creation of custom sets or experimentation with different training sets was outside the scope of the project.

Furniture arrangements or geometric features in the field of view can result in randomly-generated face and people detection false positives. Figure G 1 shows two such examples.

³⁵ The algorithms are developed to assess presence only, not occupants' identity.



Figure G 1: False occupancy reported by the face detector (left) and the people detector (right) (Luigi Gentile Polese/NREL)

The challenge is that, even using the sensor camera during commissioning, it is almost impossible to predict whether there will be false detection of faces or people. Potential preventive actions include the use of better training data sets for the detectors (generic training sets were used). In addition, an audit of the face and people detectors outputs over a period of time may be necessary to evaluate the frequency of false positives. There is also the potential for instructing IPOS to ignore the false detections by either manually inputting locations, or through a self-training software algorithm. Because false face or people detections recur at the same approximate coordinates (assuming furniture or space layout is not rearranged), allowing IPOS to generate a list of coordinates to ignore during image processing should minimize false positives. This self-training software algorithm could be re-run as furniture or space layouts change over time.

Assessment Modules Considerations

Activity Levels

A simple algorithm was used for activity level classification of occupants in demand controlled ventilation applications. The function, based on information generated by the motion detection function, gives an estimate of the overall activity level in the space—classified as sedentary or active. The activity level could be used to adjust temperature setpoints and ventilation levels. During functional test, using sample image subsets, the function was able to accurately classify between the two activity levels about 90% of the time.

However, accuracy of the activity level estimate depends on motion detection accuracy: for example, sudden light level changes (perceived in the motion detector as a large body in motion) can produce an overestimated activity level that is reported as “vigorous,” while in reality there may be no motion at all or no occupants present.

Occupant Count and Location

Occupant location was assessed during functional testing using a set of images having one occupant facing the IPOS sensor camera in an open office space. The function, based on information generated by the face and people detectors, reported the location of the occupant in polar coordinates³⁶ with 5 foot accuracy, verified with an image set used for the people detector (Figure G 2 and Table G 1).



Figure G 2: Occupancy reported from PDM (Luigi Gentile Polese/NREL)

Occupants	Frame Size (pixels)	Source	Estimated Distance (ft)	Angle (degrees)
1	320 × 240	People detector	10.3	100.0

Table G 1: Occupant Count and Location Estimate for the Frame in Figure G 2

Occupant location functionality and accuracy depends on the face and people detector functions and their accuracy.

³⁶ The origin is a fictitious point located halfway on the lower edge of the image.

Appendix H – IPOS Use Case Demonstration Setups

Daylight Harvesting and Occupancy Control

In line with project objectives, a prototype is currently deployed at a third-party location for collecting feedback on a potential daylighting harvesting and control application. When completed, the activity is expected to inform on IPOS's ability to evolve into a new potential product as highlighted above.

The IPOS prototype is configured as a combined occupancy sensor, daylight harvester, and dimming controller of two lighting zones. The occupancy and dimming outputs generated by IPOS are utilized to control the lighting power levels of a conference room (Figure H 1). The location of the installation is a lighting control and energy management solution company for commercial buildings in Colorado. The lighting energy management product, the IPOS prototype has been integrated with is comprised of cloud-based software, wireless modules embedded in existing original equipment manufacturer partner product designs, communication gateways, and network commissioning tools.

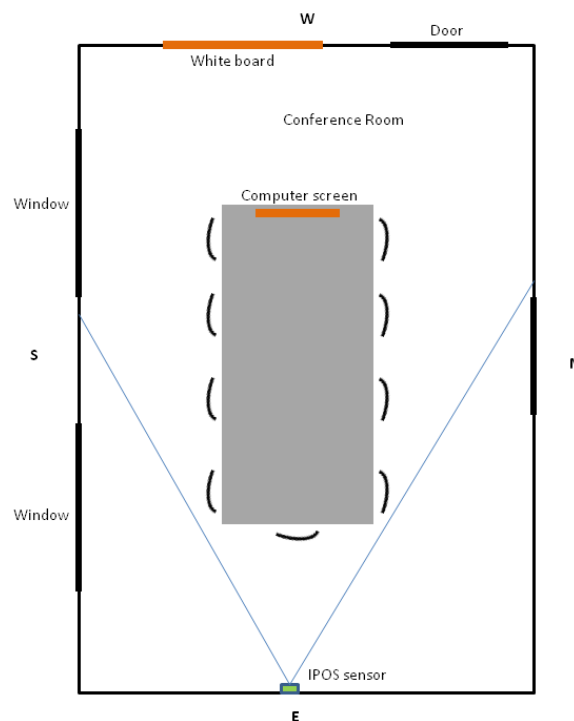


Figure H 1: Conference Room Layout for Daylighting Application (Luigi Gentile Polese/NREL)

The room receives natural light from two windows on the south-facing wall. Parking spaces for cars are immediately adjacent to the windows. The windows have manually operable venetian blinds. The room has a single manual switch controlling six fluorescent light fixtures, each controllable through individually addressable wireless ballasts. The room has no lighting or daylighting controls (no occupancy sensors or daylight harvesters), making it ideal for an early testing site. The IPOS camera sensor is

placed as indicated in Figure H 1, about 5 feet high from the floor on the east wall and facing a computer screen on the table and a white board on the wall.

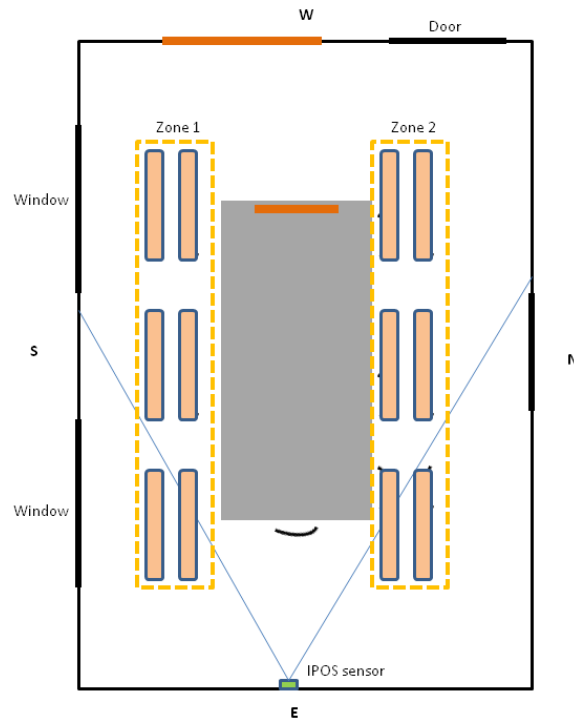


Figure H 2: Daylighting Control Zones (Luigi Gentile Polese/NREL)

The six individually-controllable room lights (through ZigBee-enabled ballasts) are grouped via software into two banks representing two daylighting zones (Figure H 2) and configured to receive dimming levels and on/off controls from the IPOS prototype through a gateway. Figure H 3 shows the two IPOS ROIs as seen from the sensor and used for measuring the illuminance levels of the work plane which are mapped to the two daylighting zones. This is in addition to whole-image (ROI 0) occupancy sensing which is used for controlling the on/off state of the lights (both zones). The light switch is left in the “on” position to allow for IPOS control.

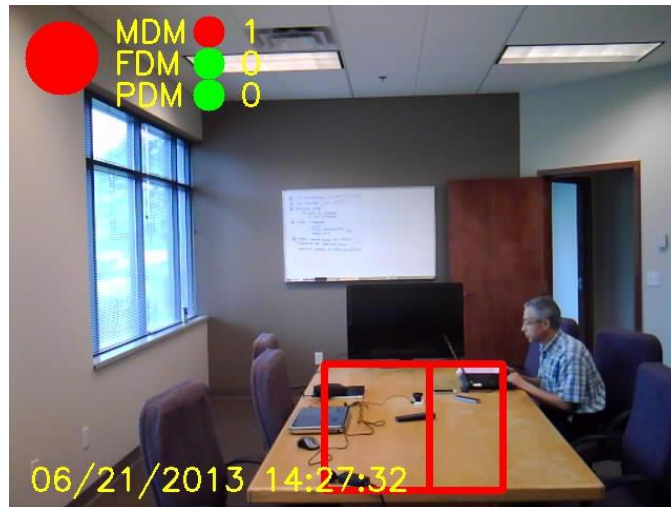


Figure H 3: IPOS ROI Zones for Daylighting Control (Luigi Gentile Polese/NREL)

The dimming outputs generated by IPOS for the two ROIs (ROI 1 and 2) control the light power levels of the conference room.

No calibration of the IPOS illuminance estimation function was performed. The calibration settings used were the same as described in Appendix A. Two illuminance setpoints were configured for continuous dimming (see Appendix B). The prototype was configured to output dimming value updates at each minute for both zones. Occupancy updates are generated by the IPOS prototype and sent to the gateway every 5 seconds. The camera sensor used for the test had a field of view of 45° , which is sufficient for covering most of the normally occupied portion of the room. Figure H 4 shows the integration between IPOS and the lighting control system.

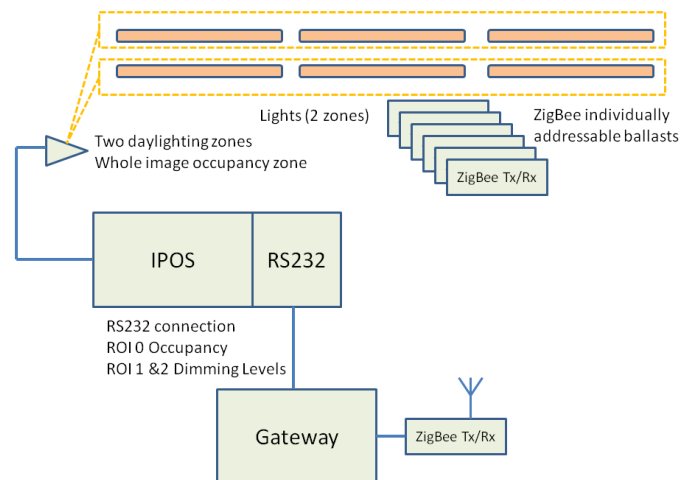


Figure H 4: Schematic Connection of IPOS for Daylighting Control (Luigi Gentile Polese/NREL)

The IPOS prototype has been modified to add support for a serial connection (RS-232C) with the gateway. In addition, the IPOS software has been extended to send the following outputs on the serial connection:

- Occupancy
- Confidence level
- Number of occupants
- Illuminance estimate
- Dimming level
- Zone coordinates

The gateway was modified to read IPOS occupancy (ROI 0), illuminance (ROI 1 and 2), and dimming levels (ROI 1 and 2) from the serial interface. Illuminance readings were only used for logging purposes at the gateway. The gateway software mapped the occupancy and dimming signals into power levels and on/off controls for the ballast receivers.

Occupancy and Event Logger, Occupancy Analysis of Walk-In Freezers

One IPOS prototype has been modified and deployed at the back of the store. The prototype was modified to monitor and log, on a continuous basis, occupancy information, and freezer door state. Figure H 5 shows the IPOS sensor's field of view at the installed location.



Figure H 5: IPOS Sensor View of the Walk-In Freezer Door (Luigi Gentile Polese/NREL)

The monitoring/logging test is expected to:

- Inform on the potential use case as a logging device (and in the future as an aggregated reporting device), and
- Inform on potential energy conservation measures from information collected regarding the door left open or partially closed outside of normal loading or unloading operations (i.e., doors left open and unattended).

The door state is monitored through a miniature Reed switch installed on the top of the door slide guide. The switch closure state generates a logical voltage level that is read and logged by the IPOS software through a general-purpose input/output interface. In a future development, the prototype may be able to detect door state through image processing. One IPOS data record consists of:

- Timestamp (date and time).
- Occupancy state (0=vacant, 1=occupied).
- Occupancy confidence level (range 0-100%).
- Door state (0=closed, 1=open).

A new data record is stored every time a change occurs either in occupancy state, door state, or confidence level. The data records are stored in a CSV file on the IPOS device and downloaded manually approximately every 1-2 months through a dedicated wireless connection. Once downloaded, the CSV file can be opened, read and processed for analysis through Microsoft Excel as a spreadsheet. Test duration is planned to be for a period of about one year.

Interactive Exhibit

NREL has plans in FY 14 to evaluate the use of an IPOS prototype as an aid for interactive audio and visual exhibits. The occupancy signals generated by the prototype will be utilized to control the brightness levels of a large touch screen exhibit at NREL's Education Center. The interactive exhibit, called the Energy Systems Integration (ESI) Visualization, will show and educate the public on several energy flows (from live data) of the NREL campus (Figure H 6). Visitors approaching the exhibit will cause the screen to go in full brightness mode. The screen returns to a dim/low-power consumption state when no visitors are in proximity of the exhibit.



Figure H 6: NREL Campus ESI Visualization Screen (Marjorie Schott/NREL)

The touch-screen exhibit is planned to be located in a medium-size area of NREL's Education Center (Figure H 7).

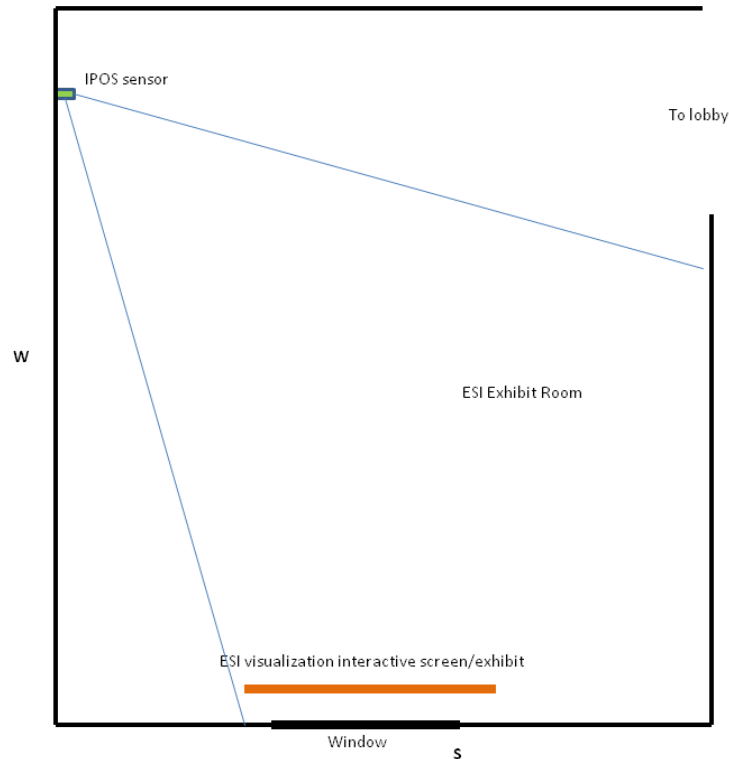


Figure H 7: NREL Campus ESI Visualization Demonstration Setup (Luigi Gentile Polese/NREL)

The room receives daylight from a window on the south facing wall. The IPOS sensor will be tentatively mounted as shown in Figure H 7, about 6 feet from the floor on the west wall and facing southeast (to exclude the area of the lobby/desk).

Other potential mounting location for IPOS is in the middle of the south wall (where the screen is located), about 6 feet from the floor and facing north. This option is potentially more desirable than the first because it allows the view of frontal faces when visitors interact with the ESI screen. The sensor may be configured with smaller ROIs to eliminate unwanted occupied areas from the camera's field of view.

The goals of the IPOS prototype used as a controller of the large screen brightness are to:

- Attract visitors' attention by turning the ESI visualization screen on when presence is detected in the room
- Save energy by dimming the screen brightness when the room is vacant

The main research goal in the short term is to inform necessary technology improvements from lessons learned from live test. Figure H 8 shows the connection between IPOS and the interactive screen.

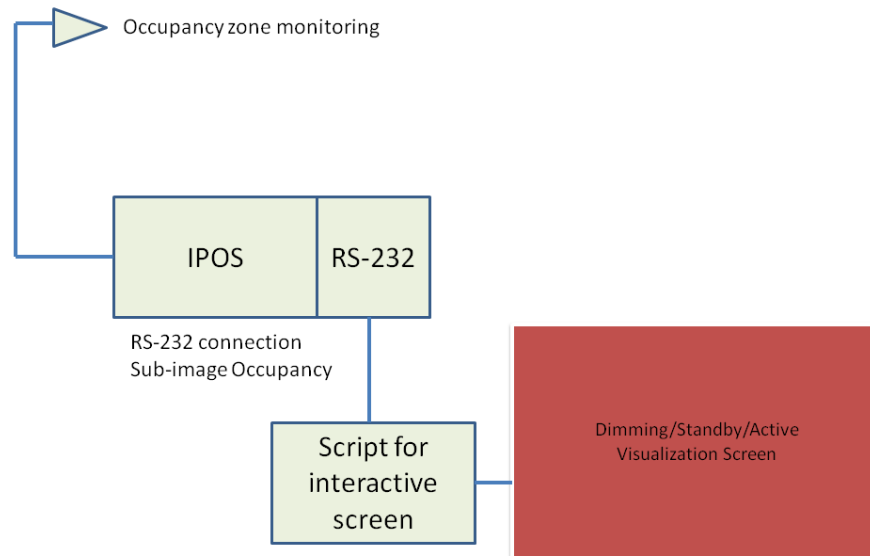


Figure H 8: IPOS Connection to ESI Visualization Demonstration Exhibit (Luigi Gentile Polese/NREL)

A user-configurable file will be provided for instructing the IPOS prototype to generate occupancy signals only. IPOS occupancy signals will be generated approximately every 5 seconds and read through a serial connection from a script running on a PC (Figure H 8). The script reads the occupancy signal, and adjusts the touch screen display brightness signal of the ESI visualization display. The exhibit and demonstration project is planned to go online after completion of this report.

Light Logging/Lighting Sub-Metering

NREL is currently involved in an emerging technology evaluation project with the US DoD in Southern California for performance evaluation of a novel electrochromic (EC) glazing product that has potential to improve occupant comfort while reducing electric lighting usage.

One of the project needs is to sub-meter existing lights to evaluate the savings impact of the EC technology. Since there is no existing sub-metering, a dedicated sub-metering infrastructure had been considered, however evaluation of costs and labor made the project team consider an alternative approach based on IPOS. In such logging/metering application, IPOS camera sensors would be placed in a way so that they include as many light fixtures in the field of view as possible³⁷. Multiple ROIs would then be configured, one for each light fixture to be logged, both before and after EC installation. The same sensors may also read illuminance levels at several workplanes through additional ROIs.

Illuminance data is collected by the individual sensors in the form of a spreadsheet, where each row includes a timestamp and estimated illuminance readings in each ROI

³⁷ Contrary to occupancy and daylighting applications, light sources should be normally avoided in the camera's field of view.

(light fixtures and workplanes). Each sensor can currently report on up to 16 ROIs³⁸. Data would then be streamed to a central server at NREL through a dedicated 4G hotspot to which the IPOS sensors in the building connect via wireless Ethernet. Pre-processing at NREL of the received data includes translating illuminance values from the light fixtures into on/off/dim levels for allowing further project-specific analysis. Although sensor placement and initial IPOS sensor setup was started at the DoD building, reliability and stability issues of the remote connection forced stop to the data collection phase and the project to re-evaluate alternative solutions for the 4G connection.

³⁸ The number of regions is modifiable through configuration; however, impact on processing performance was not evaluated.